Branched polyethyleneimine-assisted 3-carboxybenzoboroxole improved Wulff-type boronic acid functionalized magnetic nanoparticles for the specific capture of cis-diol-containing flavonoids under neutral conditions

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Flavonoids have shown a variety of biological activities such as antimicrobial, antibacterial, antifungal, antiviral, anti-inflammatory, antitumor, antiatherogenic, and anti hypertensive activities. A lot of important flavonoids contain cis-diols such as rutin (Ru), quercetin (Qu), luteolin (Lu), myricetin (Myr) and baicalin (Ba) and so on. It is necessary to establish a simple, low-cost and efficient purification method for cis-diol-containing flavonoids from plant extracts. Boronic affinity materials are able to reversibly bind the cis-diols via boronic acids by forming a five- or six-membered boronic cyclic ester in aqueous media. However, conventional boronic affinity materials have to be used in alkaline media, which can lead to the oxidation of cis-diols in compounds. In this study, the polyethyleneimine (PEI)-assisted 3-carboxybenzoboroxole-functionalized magnetic nanoparticles (MNs) were prepared to achieve efficient capture of cis-diol-containing flavonoids under neutral conditions. Branched PEI was applied as a scaffold to amplify the number of boronic acid moieties, while 3-carboxybenzoboroxole, exhibiting high affinity and excellent water solubility toward flavonoids, was used as an affinity ligand. The prepared boronic affinity MNPs exhibited high binding capacity and fast binding kinetics (equilibrium in 3 min) under neutral conditions. In addition, the obtained boronic affinity MNPs exhibited high binding affinity ($K_d = 10^{-4} \text{M}$), low binding pH (pH $\approx 6.0$) and tolerance of the interference to abundant sugars.

Introduction

Flavonoids are plant-derived dietary components defined by a diphenylpropane (C6-C3-C6) skeleton, which consist of a large group of heterogeneous polyphenols. Flavonoids can be found in fruits, vegetables, herbaceous plants, flowers, tea, honey, coffee and wine, etc. Pharmacological studies of flavonoids have shown a variety of biological activities such as antimicrobial, antibacterial, antifungal, antiviral, anti-inflammatory, antitumor, antiatherogenic, antihypertensive activities and fighting acetaminophen-mediated hepatotoxicity, especially antioxidant activities. Many biological and pharmacological properties of flavonoids are associated with free radical-scavenging actions because free radicals are considered to be important causative factors in the development of various diseases. Clearly, flavonoids are highly beneficial for human health via interacting with a number of cellular targets involved in critical cell signalling pathways in the body. A lot of flavonoids contain cis-diols such as rutin, quercetin, luteolin, myricetin, fisetin, leptosidin, aureusidin and baicalin, and so on. The type of cis-diol-containing flavonoids is unique classes of flavonoids, which exhibits a variety of biological activities. Therefore, it is extremely important to determine cis-diol-containing flavonoids in real samples such as fruits, vegetables, herbaceous plants, flowers, tea, honey, coffee, wine and so on. Spectrophotometric methods are suitable for determining cis-diol-containing flavonoids because the equipment is simple and easy to operate. However, some interfering components in the sample matrix affect the analysis. Therefore, it is necessary to establish a simple, low-cost and efficient purification method for cis-diol-containing flavonoids from plant extracts.

Boronic affinity is a unique means for the selective extraction and separation of cis-diol-containing compounds. Boronic acids are able to covalently interact with cis-diol-containing compounds to form five- or six-membered cyclic esters usually under alkaline pH conditions and the cyclic esters dissociate when the environmental pH is changed to acidic. However, the use of alkaline media is easy to oxidize the cis-diols of cis-diol-containing flavonoids. In addition, the discharge of alkaline aqueous solution may cause secondary pollution in water, which requires additional separation treatments. Thus, boronic acid-functionalized materials that can
function at neutral pH would be highly desirable for the separation and purification of cis-diol-containing flavonoids. As far as we know, a variety of attempts have been made to reduce the binding pH. Up to date, four types of boronic acid monomers with low pKₐ values can provide low binding pH: (1) boronic acid ligands with electron-withdrawing groups, such as nitro, fluoro and sulfonyl on the phenyl ring;²⁹-⁴⁰ (2) Wulff-type boronic acids, which contain intramolecular tetracoordinated B–O bonds;⁴¹-⁴³ (3) improved Wulff-type boronic acids, which contain intramolecular tricoordinated B–O bonds;⁴₄,⁴₅ and (4) heterocyclic boronic acids.⁴₅,⁴₆ The above mentioned structures of boronic acid ligands can be used to prepare boronate affinity materials with low binding pH. Among them, improved Wulff-type boronic acids, which are called benzoboroxoles, contain intramolecular tricoordinated B–O bonds rather than the classical intramolecular tetracoordinated B–N or B–O bonds in the molecular structure. Due to their unique structure, benzoboroxoles display the advantages of a low pKₐ value (7.3), excellent hydrophilicity and improved cis-diol binding capability under neutral conditions. Among the benzoboroxoles family, 3-carboxybenzoboroxole possesses lower pKₐ value (6.9) and higher affinity to cis-diol-containing compounds due to the electron-withdrawing effect of carboxyl.⁴⁷ Therefore, 3-carboxybenzoboroxole is considered as a powerful ligand to prepare boronate affinity materials. For example, researchers have prepared boronate affinity monolithic columns through using the improved Wulff-type boronic acids as ligand for the selective capture of nucleosides/glycoproteins/glycopeptides under neutral or acidic conditions.⁴⁷-⁴⁹ However, such materials have not been used in the large-scale cis-diol-containing flavonoids enrichment. In addition, the binding capacity of monolithic columns is usually lower than that of nonmaterial. Therefore, the development of 3-carboxybenzoboroxole-functionalized nanomaterials might be of great significance to achieve efficient capture of cis-diol-containing flavonoids under neutral or acidic conditions.

However, the binding capacity of single boronic acids functionalized materials toward cis-diol-containing compounds is relatively low. Through amplification of the number of boronic acid moieties using highly branched poly(amidoamine) (PAMAM) dendrimers or polyethyleneimine (PEI), the boronic acid functionalized materials exhibited a significantly improved binding capacity. Compared with PAMAM, the branched PEI can be used as a better scaffold to amplify the number of boronic acid moieties because of its flexible chains, hydrophilic properties, easy post-modification, plentiful amino groups and low cost. Thus, it is essential to develop PEI-assisted improved boronic acids-functionalized nanomaterials for the specific capture of cis-diol-containing flavonoids under neutral pH condition.

In the study, we applied 3-carboxybenzoboroxole as ligands to prepare PEI-assisted boronic acid-functionalized magnetic nanoparticles (MNPs) for highly efficient capture of cis-diol-containing flavonoids under neutral condition. In this work, magnetic Fe₃O₄ nanoparticles were used as supporting nanomaterials due to their good biocompatibility, super-paramagnetic property, low toxicity and easy preparation. Firstly, amino-functionalized MNPs were synthesized and then PEI modified MNPs were prepared. Subsequently, PEI modified MNPs were functionalized with boronic acid by the amidation between amino of PEI and carboxyl of 3-carboxybenzoboroxole. Due to the PEI-amplified boronic acid sites, the binding capacity of the obtained PEI-assisted boronic acid-functionalized MNPs was significantly enhanced. The prepared boronate affinity MNPs exhibited fast binding kinetics (equilibrium in 3 min) under neutral condition. In addition, the obtained boronate affinity MNPs exhibited high binding affinity (Kₐ = 10⁻⁴ M) and low binding pH (pH ≥ 6.0).

**Experimental**

**Reagents and materials**

Branched polyethyleneimine (PEI) (Mₙ = 600, 1800, 10 000 and 70 000), 3-carboxybenzoboroxole (CBO), rutin (Ru), quercetin (Qu), luteolin (Lu), myricetin (Myr), genistein (Gen), isorhamnetin (Iso), and kaempferol (Kae) were from J&K Scientific (Shanghai, China). Ferric chloride hexahydrate (FeCl₃·6H₂O), anhydrous sodium acetate (NaOAc), ethylene glycol, sodium cyanoborohydride, anhydrous methanol, glutaeraldehyde, 1,6-hexanediamine, 1-ethyl-3-(3-dimethylaminopropyl) carbodiimide (EDC) and N-hydroxysuccinimide (NHS) were purchased from Alfa Aesar (Tianjin, China). All used reagents were of analytical grade. All commercially available reagents were used without further purification. Water used in all the experiments was purified by a Milli-Q Advantage A10 ultrapure purification system (Millipore, Milford, USA).

**Instruments**

Transmission electron microscopy (TEM) was performed on a JEM-1010 system (JEOL, Tokyo, Japan). Powder X-ray diffraction (XRD) analyses were carried out using a Bruker D8 Advance diffractometer with Cu Kα radiation and the scanning angle ranged from 10° to 80° of 2θ. UV absorbance data were acquired from a U-3010 UV spectrophotometer equipped a 1 cm cuvette (Kyoto, Japan). The magnetic properties were measured with a vibrating sample magnetometer (VSM) (LD) 9600-1, USA). The magnetic properties were measured with a vibrating sample magnetometer (VSM) (LD) 9600-1, USA).

**Preparation of Fe₃O₄@PEI@CBO**

The procedure for the synthesis of Fe₃O₄@PEI@CBO was depicted in Fig. 1. It included three steps: (1) synthesis of amino-functionalized magnetic nanoparticles (Fe₃O₄ NPs), (2) preparation of PEI modified MNPs (Fe₃O₄@PEI), and (3) functionalization with 3-carboxybenzoboroxole (CBO). The Fe₃O₄ NPs were synthesized based on a previously reported method with minor modification. Briefly, ferric trichloride hexahydrate (2.0 g) was first dissolved in ethylene glycol (60 mL) to form a clear orange yellow color solution. Then, anhydrous sodium acetate (4.0 g) and 1,6-hexanediamine (13.0 g) was added to the
above solution. Finally, the mixture was stirred vigorously for 40 min and sealed in a PTFE-lined autoclave and reacted at 198 °C for 6 h. The resulting Fe₃O₄ NPs were rinsed with water and ethanol for 3 times each, and then dried at 50 °C in a vacuum overnight. After 200 mg Fe₃O₄ NPs were added to 40 mL anhydrous methanol containing 5% glutaraldehyde, the mixture was mechanically stirred for 12 h at room temperature. The resulting glutaraldehyde-activated Fe₃O₄ NPs were collected by a magnet and then dispersed in 40 mL anhydrous methanol containing 0.6 g PEI by ultrasound. The mixture was mechanically stirred for 12 h at room temperature. The kinetic adsorption experiment was performed as follows: the suspension containing 3 mg Fe₃O₄@PEI@CBO was added to 0.5 mL of rutin or quercetin solution and shaken different durations from 1 to 14 min at room temperature. The MNPs were collected by using external magnetic force and rinsed with 500 μL of 50 mM phosphate buffer (pH 7.0) for three times. After washing, rutin or quercetin bound on Fe₃O₄@PEI@CBO was eluted in 100 μL acetic acid solutions (pH 2.7) for 1 h on a rotator and the concentration of rutin or quercetin in the supernatant was measured by absorbance analysis.

Kinetic adsorption experiment

0.50 mg mL⁻¹ of rutin or quercetin dissolved in 50 mM phosphate buffer (pH 7.0) was applied as a representative sample. The measurement of adsorption isotherm was performed according to the following process. Briefly, Fe₃O₄@PEI@CBO was first dispersed to 50 mM phosphate buffer to homogenize the NPs (15 mg mL⁻¹). After Fe₃O₄@PEI@CBO of the above suspension (200 μL) were collected by a magnet, 300 μL solutions of different concentrations of rutin or quercetin were added to the above Fe₃O₄@PEI@CBO and shaken on a rotator for 1 h at room temperature. Thereafter, Fe₃O₄@PEI@CBO with trapped rutin or quercetin were separated by using an external magnetic force and then washed with 300 μL of 50 mM sodium phosphate buffer (pH 7.4) for 3 times each. Finally, the components bound on the NPs were eluted by 100 mM acetic acid solution. The eluent containing rutin or quercetin adsorbed by the NPs was measured with UV-vis spectrophotometer.

The Scatchard analysis was implemented according to a previously reported method.¹² Dissociation constant (Kd) and apparent maximum binding capacity (Qmax) were evaluated according to the following Scatchard equation:

\[
\frac{Q_e}{C_e} = \frac{Q_{\text{max}}}{K_d} - \frac{Q_e}{K_d}
\]

where Qmax and Kd is the saturated binding capacity and the dissociation constant, respectively, Qe is the binding amount of rutin or quercetin to Fe₃O₄@PEI@CBO at equilibrium, C_e is the free concentration at adsorption equilibrium. The values for Kd and Qmax can be calculated from the slope and the intercept of plots of Qe/C_e versus Q_e.
Reproducibility and reusability
The experiment on reproducibility of Fe3O4@PEI@CBO was carried out through adding 3 mg of five batches of dry products prepared on different time into 0.3 mL of rutin or quercetin solution at a concentration of 0.50 mg mL\(^{-1}\). The remaining steps were the same as binding isotherm experiment. To estimate the reusability of Fe3O4@PEI@CBO, 3 mg of dry MNPs was added to 0.3 mL of rutin or quercetin solution at a concentration of 0.50 mg mL\(^{-1}\) and incubated for 30 minutes at room temperature. Then, the products were separated by an external magnet. The recovered NPs were washed with 5 mL acetonitrile–acetic acid (1/2, v/v) for 2 hours to ensure complete removal of the residual quercetin in Fe3O4@PEI@CBO. Fe3O4@PEI@CBO were washed with water several times, then dried under vacuum overnight and reused for the adsorption of rutin or quercetin again. The adsorption–regeneration cycle was repeated ten times with the same Fe3O4@PEI@CBO.

Results and discussion
Characterization of the magnetic nanoparticles (MNPs)
The morphology of the prepared MNPs was characterized by transmission electron microscopy (TEM). As depicted in Fig. 2A, TEM images of Fe3O4@PEI@CBO revealed that the MNPs had good dispersibility and relatively homogeneous size distribution. The average diameter of the Fe3O4@PEI@CBO was estimated to be about 100 nm. The magnetization of the bare MNPs and Fe3O4@PEI@CBO was measured using VSM and the resulting magnetic hysteresis curves are shown in Fig. 2B. The saturation magnetizations of bare MNPs and Fe3O4@PEI@CBO were 80.32 and 71.75 emu g\(^{-1}\), respectively, which indicates superparamagnetic behavior. The decrease of the saturation magnetization of Fe3O4@PEI@CBO in comparison with bare MNPs results from the formed modification layers, which could shield the magnetite to some extent. The crystalline nature of Fe3O4@PEI@CBO has also been confirmed by XRD analysis (Fig. 3), considering the several sharp peaks corresponding to the crystalline planes of cubic spinel nanostructure of the magnetic nanoparticles.

Selectivity
The selectivity of the obtained Fe3O4@PEI@CBO was first investigated using rutin (Ru), quercetin (Qu), luteolin (Lu) and myricetin (Myr) as cis-diol-containing test flavonoids and genistein (Gen), isorhamnetin (Iso), and kaempferol (Kae) as non-cis-diol analogue. As depicted in Fig. 4, Fe3O4@PEI@CBO exhibited higher binding capacity for cis-diol-containing flavonoids than that for non-cis-diol flavonoids, which indicated good selectivity.

Optimization of the molecular weight of PEI
Generally, the larger the molecular weight of PEI is, the more amine groups it can provide. However, once the molecular weight of PEI exceeds a certain value, a portion of amine groups may become inaccessible. Thus, it is necessary to investigate the effect of the molecular weight of PEI on the number of the binding sites. The number of the binding sites can be reflected by binding capacity (Q, mg g\(^{-1}\)). To determine which molecular weight of PEI can obtain the highest binding capacity, we investigated the effect of the chain length of PEI on the binding capacity. It should be noted that the amount of functional monomer can be guaranteed to be excess. We investigated which amount of functional monomer is excess for the adsorption capacity before optimizing the molecular weight of PEI. As depicted in Fig. 5, the binding capacity increased with...
the increase of molecular weight of PEI from 600 to 10,000 regardless of Ru or Qu. However, when PEI 70,000 was used, the binding capacity is lower than that when using PEI 10,000. The PEI 10,000-modified 3-carboxybenzoboroxole-functionalized MNPs were considered as the optimal Fe₃O₄@PEI@CBO for further investigations and application.

**Determination of \( Q_{\text{max}} \) and \( K_d \)**

Binding capacity is a crucial factor in boronate affinity materials. It determines the maximum amount of targets that an affinity material can capture. On the other hand, binding affinity is an important binding property of boronate affinity materials, which can determine how low the concentrations of cis-diol-containing flavonoids can be enriched by Fe₃O₄@PEI@CBO. The maximum binding capacity (\( Q_{\text{max}} \)) and dissociation constant (\( K_d \)) of Fe₃O₄@PEI@CBO with rutin (\( M_w: 610 \)) and quercetin (\( M_w: 302 \)) were evaluated using UV-vis spectrophotometry.

We first investigated binding capacity and binding strength of Fe₃O₄@PEI@CBO toward rutin. As shown in Fig. 6, according to binding isotherms and Scatchard plots analyses, \( Q_{\text{max}} \) and \( K_d \) values of Fe₃O₄@PEI@CBO were calculated to be \((3.21 \pm 0.23) \text{ mg g}^{-1}\) and \((1.01 \pm 0.10) \times 10^{-4} \text{ M}\), respectively. We further investigated the binding capacity and binding strength of the Fe₃O₄@PEI@CBO toward quercetin. The binding isotherms and Scatchard plots for quercetin were shown in Fig. 7. The \( Q_{\text{max}} \) and \( K_d \) values of Fe₃O₄@PEI@CBO were evaluated to be \((4.29 \pm 0.21) \text{ mg g}^{-1}\) and \((3.62 \pm 0.21) \times 10^{-4} \text{ M}\), respectively. Clearly, the rutin exhibited nearly four folds lower \( K_d \) value than quercetin for Fe₃O₄@PEI@CBO. This possible
explanation is that as rutin contains a pair of cis-diols, there is synergistic effect on the Fe₃O₄@PEI@CBO to some extent, which can greatly improve binding strength of Fe₃O₄@PEI@CBO toward rutin. In contrast, quercetin contains only one cis-diol group, there is no synergistic effect on the Fe₃O₄@PEI@CBO. Clearly, the reason for the lower binding constant of the Fe₃O₄@PEI@CBO toward quercetin is the absence of synergistic effect of multiple binding. In addition, the K_d value for rutin is also a little lower than those the previous boronate affinity materials provided for other single cis-diol such as adenosine due to synergistic effect.

However, although rutin exhibited higher binding affinity than quercetin for Fe₃O₄@PEI@CBO, the Q_max of rutin was a little lower than that of quercetin (Table 1). This is because that rutin occupies more binding sites of boronic acid moieties as compared with quercetin.

Table 1 Dissociation constants (K_d) and binding capacity (Q_max) of Fe₃O₄@PEI@CBO for Ru and Qu

|       | K_d [M]          | Q_max [μmol g⁻¹] | R²   |
|-------|------------------|------------------|------|
| Ru    | (1.01 ± 0.10) × 10⁻⁴ | 3.21 ± 0.23      | 0.94 |
| Qu    | (3.62 ± 0.21) × 10⁻⁴ | 4.29 ± 0.21      | 0.98 |

In a word, the amplified number of boronic acid moieties by using PEI as a scaffold can improve greatly the binding affinity of Fe₃O₄@PEI@CBO toward flavonoids with multiple cis-diols but fails to improve even reduce the binding capacity.

**Adsorption time**

An appropriate adsorption time to obtain high binding capacity is required in the extraction and separation procedure. The effect of extraction time on the extraction efficiency of flavonoids was investigated by varying from 1 min to 10 min (Fig. 8). As depicted in Fig. 8, the binding capacity of Ru or Qu onto Fe₃O₄@PEI@CBO had a fast adsorption rate within the first 2 min because amount of binding sites at the beginning enabled Ru or Qu to be easily adsorbed to Fe₃O₄@PEI@CBO with less resistance. Besides, the binding capacity reached a maximum value at an adsorption time of 3 min. When the extraction time was increased from 3 to 6 min, the binding capacity remained essentially constant. These results indicate that extraction equilibrium could be achieved in 3 min, implying that most of the binding sites had been occupied by Ru or Qu in such a situation. This total adsorption time in the prepared boronate affinity materials is much shorter than that in other boronate affinity materials (30–90 min). This may be ascribed to its excellent adsorption of flavonoids during the extraction. In the light of these results, 3 min was chosen as the optimum adsorption time for extraction. This result indicates that the mass transfer speed in the Fe₃O₄@PEI@CBO prepared by the proposed method was fast.

**The lowest extractable concentration of rutin and quercetin**

As we know, binding strength can determine how low extractable concentration of cis-diol-containing flavonoids. As Fe₃O₄@PEI@CBO exhibited significantly increased binding affinity towards rutin due to the amplified number of boronic acid

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**Fig. 7** Binding isotherms (A) and Scatchard plots (B) for the binding of Fe₃O₄@PEI@CBO with quercetin (Qu).

**Fig. 8** Binding equilibrium of Fe₃O₄@PEI@CBO with Ru and Qu. Sample: 0.50 mg mL⁻¹ Ru containing 50 mM phosphate, pH 7.0.
moieties, Fe₃O₄@PEI@CBO were able to extract rutin of lower concentration than quercetin. To investigate the lowest extractable concentration of rutin and quercetin, UV-vis absorbance was used. As shown in Fig. 9, for rutin and quercetin standard solutions, the lowest detectable concentrations were 0.3 μg mL⁻¹ (S/N = 5.0) and 0.2 μg mL⁻¹ (S/N = 7.0), respectively. When the detection was combined with the Fe₃O₄@PEI@CBO extraction, the lowest detectable concentrations for rutin and quercetin were lowered to 0.003 μg mL⁻¹ (S/N = 12) and 0.01 μg mL⁻¹ (S/N = 12), respectively. The results indicated that the Fe₃O₄@PEI@CBO were able to extract lower concentration of rutin as compared with other single cis-diol such as quercetin.

**Effect of competing saccharides on the extraction of flavonoids by Fe₃O₄@PEI@CBO**

Sugars, cis-diol-containing compounds, are present in real samples such as in fruits, vegetables, herbaceous plants, tea, honey, coffee and, thus, their competing binding with boronic acids may result in reduced extraction capabilities of boronic acid-functionalized materials towards flavonoids. The Fe₃O₄@PEI@CBO exhibited much higher binding affinity towards flavonoids as compared with their affinity towards saccharides because flavonoids contain phenols while saccharides contain aliphatic alcohol. Thus, the Fe₃O₄@PEI@CBO was very tolerant of the interference of competing saccharides. As shown in Fig. 10, even in the presence of a competing monosaccharide at 100-fold higher concentration, the Ru and Qu amount extracted by the Fe₃O₄@PEI@CBO was 84–97% and 66–89% of that when no sugar was present, respectively, depending on the nature of the competing saccharide. Clearly, the binding of Ru to Fe₃O₄@PEI@CBO is affected less than that of Qu to Fe₃O₄@PEI@CBO by the presence of the competing saccharide.

**Binding pH**

Binding pH is an important binding property of boronic acid-functionalized materials. As most commercially available boronic acid ligands are generally weak acids with a pKₐ of 8–9, conventional boronic acid-functionalized nanomaterials require a basic binding pH. It is a common sense that the binding affinity of boronate affinity materials increased with increasing the pH. Therefore, the binding affinity is certainly better at alkaline pH than neutral pH or acidic pH. However, the basic pH is easy to oxidize the cis-diols of cis-diol-containing flavonoids. To address this issue, relatively low binding pH

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**Fig. 9** The lowest extractable concentration of Ru (A) and Qu (B).

**Fig. 10** Effect of competing saccharides on the Ru (A) and Qu (B) amount extracted by the Fe₃O₄@PEI@CBO. Samples: (A) 2 μg mL⁻¹ Ru without or with 0.2 mg mL⁻¹ saccharide; (B) 2 μg mL⁻¹ Qu without or with 0.2 mg mL⁻¹ saccharide, fructose (Fru), fucose (Fuc), mannose (Man), galactose (Gal), glucose (Glu), xylose (Xyl).
should be applied. Several boronic acid ligands with electron-withdrawing groups, such as DFFPBA and 3-carboxybenzoboroxole\textsuperscript{24,25} reduced the binding pH to neutral or acidic conditions. Thus, the prepared boronic acid-functionalized MNPs using 3-carboxybenzoboroxole as a ligand and PEI as a scaffold can provide a lower binding pH. As depicted in Fig. 11, the Fe$_3$O$_4$@PEI@CBO NPs exhibit high binding capacity and can well capture rutin or quercetin at pH $\geq 6.0$. When the pH is higher than 6.0, the binding capacity of Fe$_3$O$_4$@PEI@CBO for rutin is lower than that for quercetin because one rutin molecule can occupy only one boronic acid site. However, when the pH is lower than 5.0, the binding capacity of Fe$_3$O$_4$@PEI@CBO for rutin is higher than that for quercetin because binding affinity dominates binding capacity under lower pH conditions.

**Reproducibility and reusability**

The reproducibility of the obtained Fe$_3$O$_4$@PEI@CBO was investigated by using six batches of Fe$_3$O$_4$@PEI@CBO prepared on different days, and the measurements replicated three times in parallel. By calculation, the average $Q$ of the total six batches of Fe$_3$O$_4$@PEI@CBO for Ru and Qu were 3.02 and 3.85 mg g$^{-1}$, and the relative standard deviations (RSD) were less than 5.1% (3.8%, 4.6%, 4.8%, 4.2%, and 5.1%) for Ru and less than 6.1% (5.3%, 4.5%, 6.1%, 5.8%, 4.9%, and 5.8%) for Qu. The results indicated that the reproducibility of the Fe$_3$O$_4$@PEI@CBO was satisfactory.

A stable adsorption performance is one of the most important properties of boronate affinity materials in real application. The Fe$_3$O$_4$@PEI@CBO could be reused after washing with acid solution. The adsorption–regeneration cycle was repeated ten times with the same Fe$_3$O$_4$@PEI@CBO to evaluate the stability of the Fe$_3$O$_4$@PEI@CBO. Fe$_3$O$_4$@PEI@CBO are very stable and adsorption capacity still maintain at almost a steady value of 92.6% of the first cycle after five adsorption–desorption cycles. That’s, the Fe$_3$O$_4$@PEI@CBO could be well reused at least five times.

**Fig. 11** pH on the effect of the binding capacity of Fe$_3$O$_4$@PEI@CBO towards Ru and Qu.

**Conclusions**

In this study, the high boronate avidity SNPs were prepared for the selective enrichment of trace glycoproteins. By using branched PEI as the scaffold for amplification of boronic acid sites and 3-carboxybenzoboroxole as the affinity ligand, high boronate avidity was obtained owing to PEI-assisted synergistic multivalent binding. The obtained binding constant is $10^{-7}$ M, which was the highest among already reported boronic acid-functionalized materials except MIPs. Besides, PEI-assisted synergistic effect can lead to lower binding pH. Due to the enhanced binding strength and the lower binding pH, the boronate avidity MNPs can be directly applied to selective enrichment of trace glycoproteins from real samples.

**Conflicts of interest**

There are no conflicts to declare.

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