# Electronic Supplementary Information (ESI)

**Table S1. Comparative Analysis of Phage Immobilization Techniques**

| Category | Method | Control Principle | Advantages | Limitations | Ref. |
|---|---|---|---|---|---|
| **Physical adsorption** | Passive adsorption | Non-specific hydrophobic & van der Waals interactions | Simple operation; Extremely low cost | Weak binding strength; Prone to desorption; Random orientation | [7,13] |
| **Electrostatic interaction** | PEI / APTES coatings | Utilization of head–tail charge differences (dipole moment) | Low cost; Enables preliminary macroscopic orientation | Stability sensitive to pH/ionic strength; Non-specific adsorption | [22,24, 26] |
| **Chemical covalent bonding** | EDC/NHS coupling; Glutaraldehyde | Formation of stable covalent bonds with capsid residues | Strong binding; High environmental stability; Good reproducibility | Random coupling sites (e.g., lysine amines); Limited control over orientation | [30,28, 18] |
| **Biological affinity** | Biotin–avidin / Streptavidin | High-specificity biomolecular recognition | Excellent specificity; Orientation control; Mild reaction conditions | High cost of reagents; Potential steric hindrance | [33] |
| **Genetic affinity** | Phage display; Si-Tag | Genetically programmed self-anchoring to specific materials | Endogenous control; No chemical modification required; Programmable | Requires genetic engineering; Expression efficiency may vary | [34,35] |
| **Bioorthogonal chemistry** | Click chemistry | Site-specific reaction with noncanonical amino acids | Atomic-level precision; Full control over site/density/ orientation | High technical threshold; Requires advanced protein engineering | [37] |

**Table S2. Case Studies of Integration Between Sensing Methods and Signal Transduction Technologies**

| Sensing Method | Transduction | Specific Technique | Measured Signal | Core Principle & Features | Ref. |
|---|---|---|---|---|---|
| **Immobilization-based Capture** | Mass-sensitive | QCM-D | Resonant frequency shift (Δf) | Label-free, real-time monitoring of mass changes; provides kinetic information. | [111] |
| | Optical | SPR | Resonance angle shift (Δθ) | Label-free, real-time, high-sensitivity surface detection; high instrumentation cost. | [61] |
| | Electrochemical | EIS | Interfacial impedance (Z) | Label-free, high-sensitivity interface detection; sensitive to non-specific binding. | [105] |
| **Phage Amplification** | Optical | Colorimetric (LFA) | Visible color band | Sequential amplification and detection; portable, low cost, suitable for endpoint field detection. | [39] |
| **Reporter Phages** | Optical | Fluorescence (NanoLuc) | Photon emission | Enzymatic signal amplification; ultrahigh sensitivity, down to single-cell level. | [96],[44] |
| | | Colorimetric (CCP, ALP) | Absorbance change | Enzymatic generation of colored products; intuitive readout, suitable for low-cost applications. | [98],[99] |
| | Electrochemical | Amperometry (ALP) | Current (I) | Enzymatic generation of electroactive products; high amplification, accurate quantification. | [107],[108] |