Supporting information

Table S1 Characteristics and key biological functions of each material.

Materials	Particle size(nm)	Drug Loading/Release (%)	Drug Release Characteristics	Key Biological Effects	Ref.
M+H@ZIF/HA	176.3 ± 1.6	16.4%/79 % 4.2%/77%	pH-responsive release (TME triggered)	Anti-tumor immunotherapy; abrogates MDSC-mediated T cell paralysis, induces apoptosis-pyroptosis transition; downregulates immunosuppressive factors, enhances CD8+ T cell infiltration and activation, remodels TME.	65
IR820@ZIF-8	120	34.4%/-	Photothermal-responsive release	Tumor-targeted photothermal therapy; upregulates tumor antigen exposure, promotes DC maturation and IL-12 secretion, enhances cross-presentation; activates CTL-mediated anti-tumor immunity, significantly inhibits distant metastasis formation.	66
AZ-P@P	267	-	Acidic environment-responsive release	Specifically blocks PD-L1/PD-1 interaction, reduces T cell exhaustion; induces tumor cell ICD, releases DAMPs (HMGB1, CALR); increases tumor-infiltrating CD8+ T cells, reduces Tregs, strengthens anti-tumor immune memory.	67
LOX@ZIF-8@MPN	200	6.5%/44%	ATP/Acidic pH dual-responsive release	Efficiently consumes TME lactate, reverses abnormal angiogenesis; generates •OH via Fenton reaction, enhances CDT; induces ICD, activates cGAS-STING pathway to upregulate IFN-I, synergistically enhances anti-tumor immune response.	68

Materials	Particle size(nm)	Drug Loading/Release (%)	Drug Release Characteristics	Key Biological Effects	Ref.
PMIR	295	7.36%/-	TME-responsive release	Blocks tumor glutamine metabolism, inhibits proliferation and energy supply; downregulates PD-L1 expression, blocks immune escape; induces ICD, promotes DC maturation and T cell infiltration, converts "cold" to "hot" tumors.	69
RNA-DOX@ZIF-8	412.66 ± 12.65	7.65%/76.19%	Sustained slow release	Chemo-gene synergistic therapy; DOX kills tumor cells and induces ICD; PD-L1 siRNA silences target gene; promotes bone regeneration factors (BMP-2, Runx2), inhibits tumor recurrence signals; anti-tumor & bone repair.	70
Bc@AZTF	300	-	ATP-responsive release (intracellular ATP triggered)	Inhibits CD73-mediated ATP-adenosine conversion, reduces immunosuppressive adenosine; enhances NK & CTL tumoricidal activity, reduces M2 macrophages; induces ICD, amplifies anti-tumor immunity, inhibits growth & metastasis.	71
Vir-ZM@TD	160	10 wt%/89%	Intracellular ATP-responsive release	Mimics herpesvirus activating innate immunity, induces mtDNA stress; activates cGAS-STING pathway, promotes IFN-γ, TNF-α secretion; enhances innate immune cell (NK, macrophage) activity, establishes long-term anti-tumor immune barrier.	72

Materials	Particle size(nm)	Drug Loading/Release (%)	Drug Release Characteristics	Key Biological Effects	Ref.
ZIF-8@MnO2	248.3	-	TME-responsive degradation releasing Mn^{2+}	Specifically degrades mutant p53 protein, relieves immune pathway suppression; activates cGAS-STING pathway, promotes IFN-I secretion and DC maturation; synergizes with PD-L1 inhibitor (≈80% tumor inhibition in breast cancer), reduces lung mets.	73
CM-ZIF-8@Ce6/Lon	131.1	7.32%/81% 16.03%/83%	TME-responsive release	Lonidamine inhibits aerobic glycolysis, ameliorates hypoxia; Ce6 mediates PDT generating ROS, induces ICD; synergistically regulates macrophage M1 polarization, enhances CD8+ T cell infiltration, improves PDT-induced immunotherapy efficacy.	74
PIC/CA4@ZIF-8/HA	148±1	8.6%/-	Sustained release	CA4 disrupts tumor vasculature, blocks nutrient supply, induces apoptosis; PIC activates TLR3, promotes DC maturation & IL-12 secretion; synergistically promotes macrophage M1 polarization, enhances anti-melanoma immunity, prolongs survival.	75
HA/ZIF-8@Gem/D-1-MT NPs	195.19±1.84	8.8%/82.87% 9.14%/-	Targeted responsive release	Gem directly kills osteosarcoma cells and induces ICD; D-1-MT blocks IDO-kynurenine immunosuppressive pathway; enhances DC antigen presentation, promotes T cell proliferation & IFN-γ secretion; reduces lung metastasis, improves response rate.	76

Materials	Particle size(nm)	Drug Loading/Release (%)	Drug Release Characteristics	Key Biological Effects	Ref.
CBZP	200	36.6 μmol/g/85.86% 1.8 μmol/g/65.2%	pH-sensitive release	Curcumin blocks autophagy, enhances ICD; BMS1166 inhibits PD-L1/PD-1 interaction, restores T cell function; synergistically upregulates CALR, HMGB1, promotes DC maturation, improves osteosarcoma treatment, reduces recurrence.	77
α-Galcer/DOX@ZIF-8@HA	200	7.02%/88% 0.47%/80%	Acidic TME-responsive release	α-Galcer specifically activates NKT cells, secretes IFN-γ, IL-4; DOX induces hepatocellular carcinoma apoptosis releasing tumor antigens; synergistically remodels TME.	78
CuZPMn@DOX	115	20%/71.2%	NIR photothermal-responsive burst release	PTT/PDT/Chemo/Immuno quadruple therapy; PDA mediates mild PTT (42-45°C), PpIX generates ROS, DOX kills tumor cells; CpG activates TLR9, promotes DC maturation; significantly inhibits tumor growth (>85%), blocks lymphatic metastasis, enables MR imaging tracking.	79
ZIF-8@NDV+T/SM	-	-	Targeted release of viral particles	Novel nanovaccine carrier, protects NDV from enzymatic degradation; NDV infects and lyses tumor cells releasing antigens; activates innate & adaptive immunity, produces specific antibodies & memory T cells, establishes long-term immunity.	80

Materials	Particle size(nm)	Drug Loading/Release (%)	Drug Release Characteristics	Key Biological Effects	Ref.
ZANPs	80	30.6%/80%	pH-dependent release (APC acidic environment)	Efficiently delivers antigen to DC endosomes, protects antigen; promotes DC maturation (CD80+CD86+ up to 36%), enhances cross-presentation; induces strong humoral (specific antibodies) and cellular (CTLs) immunity; efficient vaccine delivery system.	81
OVA@ZIF-8-CpG	-	7%/90%	pH-responsive release, protects antigen	CpG ODNs activate DC TLR9 signaling, OVA as model antigen induces specific immunity; prolongs antigen circulation, enhances immune response duration; induces OVA-specific CD8+ T cell proliferation, long-term memory; efficient subunit vaccine carrier.	82
IMDQ@OVA-TA	316.5	-/81% -/29%	Sustained slow release	IMDQ activates TLR7/8 signaling, promotes DC IL-6, TNF-α secretion; enhances vaccine immunogenicity, promotes OVA-specific antibodies; induces tumor-specific CTL activity, inhibits tumor growth; provides new strategy for tumor vaccines.	83
ZIF-7/8-ADA NPs	99.41±18.86	573.2 μg/mg/96%	Acidic-responsive release (APC trigger)	Enhances vaccine stability, prolongs half-life; promotes APC uptake & antigen processing, accelerates DC maturation; induces high levels of PRV-specific neutralizing antibodies, activates cellular immunity, prevents PRV infection.	84

Materials	Particle size(nm)	Drug Loading/Release (%)	Drug Release Characteristics	Key Biological Effects	Ref.
mEHGZ	133.92± 2.93	-	TME-responsive release	GOx consumes glucose producing H_2O_2, hemin catalyzes Fenton reaction producing •OH, synergizes with EPI to enhance ICD; significantly improves TNBC tumor inhibition rate (86.7%), downregulates PD-L1; promotes DC maturation & CD8+ T cell infiltration, reduces Tregs & MDSCs, reprograms TME, improves anti-PD-L1 response.	85
UCNP@ ZIF-8	70	-	NIR-responsive release (980nm laser activates PA trigger)	Utilizes UCNP upconversion to cross BBB; MT modulates central immune system, inhibits microglial activation & pro-inflammatory cytokines (IL-6, TNF-α); reduces neuroinflammation, improves depressive-like behavior in inflammation-related depression model.	86
TA@ZIF-8	80	10%/62.5 %	Sustained release	TA exerts antibacterial effects (inhibits E. coli, S. aureus), inhibits NF-κB pathway; promotes fibroblast proliferation & collagen deposition, accelerates angiogenesis; shortens full-thickness wound healing time (3-5 days earlier), enhances tissue strength; antibacterial-anti-inflammatory-tissue regeneration synergy.	87

Materials	Particle size(nm)	Drug Loading/Release (%)	Drug Release Characteristics	Key Biological Effects	Ref.
TNT-ZIF-67@OGP	189 ± 21	5.6% wt%/95%	Acidic environment-sensitive release	Broad-spectrum antibacterial (inhibits E. coli, S. aureus, MRSA), disrupts biofilms; OGP promotes MSC osteogenic differentiation (Runx2, OCN upregulation); inhibits inflammatory cytokines (IL-1β, IL-6), enhances osseointegration; for orthopedic implant surface modification.	88
MOFs@PVA	76.4	-	Controlled release of Zn^{2+} ions	Zn^{2+} disrupts bacterial cell membrane, antibacterial; inhibits inflam·matory cell infiltration & pro-inflammatory cytokine secretion; promotes angiogenesis & collagen deposition, accelerates wound healing, enhances tissue tensile strength; for wound dressings.	89
EGCG-POL@LZIF-8	175±3.50 nm	48.5/%88%	Sustained release	EGCG inhibits IL-6, TNF-α secretion in THP-1 macrophages, modulates NF-κB/MAPK pathways; significant inhibition against E. coli, S. aureus, MRSA; enhances wound antioxidant capacity, reduces oxidative stress, accelerates infected wound healing.	90

Materials	Particle size(nm)	Drug Loading/Release (%)	Drug Release Characteristics	Key Biological Effects	Ref.
GelMA/HAMA/BP@ZIF-8	71 ± 7.65	-	Photothermal-responsive release	BP mediates PTT (temperature to 43°C under NIR), synergizes with EGCG enhancing antibacterial effect; induces macrophage M2 polarization, secretes anti-inflammatory (IL-10) & osteogenic (BMP-2) factors; promotes MSC osteogenic differentiation, accelerates bone defect repair; PTT-antibacterial-anti-inflammatory-osteogenesis synergy.	91
MCC@ZIF-8@Cur	200	-	Thermo-responsive release (body temperature trigger)	Curcumin inhibits NLRP3 inflammasome activation, reduces IL-1β secretion; antibacterial & inhibits biofilm formation; modulates diabetic wound microenvironment, promotes fibroblast proliferation & re-epithelialization, shortens healing time, reduces infection recurrence.	92
MOF/PVDF	-	23.2%/54.85%	Controlled release	As wound dressing enables sustained curcumin release; curcumin exerts antibacterial (Gram+/-) & anti-inflammatory effects, modulates MAPK pathway; promotes granulation tissue growth & angiogenesis, improves biocompatibility & efficacy; for chronic wound care.	93

Materials	Particle size(nm)	Drug Loading/Release (%)	Drug Release Characteristics	Key Biological Effects	Ref.
ZIF-8-ICG@MNs	123.17	19.67%/-	pH-responsive release (acne lesion acidic environment)	ICG mediates PDT generating ROS, disrupts C. acnes cell membrane; synergizes with ZIF-8 antibacterial action, clears acne bacteria; inhibits inflammatory cytokines (IL-8, TNF-α), reduces acne inflammation & redness, disrupts biofilms, reduces recurrence.	94
TNT-ZO	302±24	7.8%/-	Acidic-responsive release	Efficiently clears MRSA (>95% killing), disrupts biofilm structure; inhibits inflammatory cytokines, reduces peri-implant inflammation; OGP promotes MSC osteogenic differentiation & bone matrix deposition, enhances osseointegration; addresses orthopedic implant-related infection.	95
CCM@ZIF-8@SA-Composite Hydrogels	427	76.7%/25.9% (encapsulation efficienc)	Slow release	Curcumin exerts broad-spectrum antibacterial action, inhibits bacterial growth & biofilm formation; inhibits NF-κB pathway, reduces inflammatory mediators; dressing has good water absorption & breathability, promotes granulation tissue growth, accelerates infected wound healing; for chronic wound care.	96

Materials	Particle size(nm)	Drug Loading/Release (%)	Drug Release Characteristics	Key Biological Effects	Ref.
Ac@ZIF8/AgNPs	122	76.64%/79.12%	pH-responsive release (infected microenvironment trigger)	Allicin & AgNPs synergistically disrupt bacterial cell membrane, clear resistant bacteria like MRSA; AgNPs clear wound ROS, reduce oxidative stress; inhibits inflammatory cytokines (IL-6, TNF-α), promotes fibroblast proliferation & re-epithelialization, accelerates infected wound healing, reduces scarring risk.	97
PCL/LIG/ZIF-8 composite nanofibers	-	-	Sustained release of Zn^{2+} ions	Lignin exerts antioxidant effect, scavenges ROS; Zn^{2+} inhibits bacterial growth & participates in immune cell differentiation; promotes MSC osteogenic differentiation (increased ALP activity), accelerates bone defect repair, improves bone mechanical properties; for bone tissue engineering scaffolds.	98
ZIF-8@Rutin	-	-/72%	Sustained release	Rutin inhibits NF-κB & MAPK pathways, reduces IL-6, TNF-α; significant antibacterial activity against E. coli, S. aureus; scavenges wound ROS, induces macrophage M2 polarization, promotes collagen deposition & angiogenesis, accelerates infected wound healing, improves tissue quality.	99

Materials	Particle size(nm)	Drug Loading/Release (%)	Drug Release Characteristics	Key Biological Effects	Ref.
NBIF@ZIF-8/PHG	300	76.5%/73%	pH-responsive release (OA inflammatory microenvironment)	NBIF modulates synovial macrophage metabolism, inhibits pro-inflammatory cytokines (IL-1β, TNF-α); promotes chondrocyte proliferation & type II collagen synthesis, inhibits cartilage matrix degradation; improves joint swelling & cartilage damage in OA model, delays progression; immunomodulatory-cartilage protective synergy.	100
IA-ZIF-8@HMs	79.57 ± 7.89	-	Slow sustained release (hydrogel microsphere regulated)	IA inhibits synovial inflammation, reduces ROS & inflammatory factors; modulates chondrocyte metabolism, protects cartilage matrix integrity; enhances cartilage regeneration, improves joint function in OA; provides treatment for inflammation-related cartilage injury.	101
KZIF@HA	220	-	Sustained release	Kartogenin promotes cartilage progenitor cell differentiation into mature chondrocytes; inhibits synovial inflammatory cell infiltration & pro-inflammatory factors; protects articular cartilage from degradation, improves joint mobility in OA model, delays cartilage degeneration.	102

miR-200c-3p@ZIF-8	121	60.35%/82% (encapsulation efficienc)	Weak acidic environment on-demand release	miR-200c-3p regulates early OA inflammation, targets key inflammatory pathway genes; promotes chondrocyte proliferation & matrix synthesis, inhibits apoptosis; improves cartilage repair microenvironment, accelerates cartilage repair, reduces OA progression risk.	103

Materials	Particle size(nm)	Drug Loading/Release (%)	Drug Release Characteristics	Key Biological Effects	Ref.
RES/CellROX@ZIF-8	122	38.86%/90%	ROS-responsive release (inflammatory site ROS trigger)	RES induces macrophage M2 polarization, inhibits iNOS activity & NO production; CellROX specifically recognizes site ROS triggering release; synergistically inhibits IL-6, TNF-α secretion, diagnoses & precisely treats OA; theranostics.	104
CAT&SMT@ZIF-8-Ab	160	0.44 mg/mg/83% 1.38 mg/mg/50%	Responsive release	CAT clears excess H_2O_2 in joint, reduces oxidative stress; SMT inhibits iNOS activity, reduces NO production; synergistically protects chondrocytes from inflammatory damage, inhibits cartilage matrix degradation, improves OA joint inflammation & dysfunction.	105

Fe/ZIF-8/Gel	600	-	Sustained release of Zn^{2+}&catalytic substances	Multi-enzyme mimic activity, efficiently clears joint ROS; generates dissolved oxygen improving hypoxic microenvironment; provides joint lubrication, reduces cartilage friction damage; synergistically inhibits inflammation, promotes cartilage repair; multi-target OA therapy.	106
miR/IrO2 @ZIF-8	210	13.4% (w/w)/83 %	Responsive release	IrO_2 has multi-enzyme mimic activity, clears joint ROS & RNS; AntagomiR-181a downregulates pro-inflammatory miRNA expression, inhibits inflammatory signaling; balances chondrocyte anabolic/catabolic metabolism, reduces cartilage damage, improves OA symptoms, delays progression.	107

Materials	Particle size(nm)	Drug Loading/Release (%)	Drug Release Characteristics	Key Biological Effects	Ref.
MOF@PH	170	20.13 wt%/59%	pH-responsive release (acidic IVD degeneration site)	Protocatechuic acid inhibits nucleus pulposus cell inflammation, downregulates IL-6, ROS; inhibits NP cell apoptosis & matrix degrading enzyme (MMP-13) activity; protects IVD tissue integrity, delays degeneration, alleviates pain.	108

SC:ZIF-8	220	22.5%/73.89%	pH-dependent sustained release	Scopoletin improves solubility & bioavailability, enhances anti-inflammatory activity; inhibits NF-κB pathway, reduces pro-inflammatory factors; scavenges ROS, reduces oxidative stress, protects tissue function; for inflammatory diseases.	109
SFZ	-	5.6 wt%/-	Weak acidic inflammatory environment-responsive release	Cascade enzyme activity clears ROS at inflammatory sites, reduces oxidative stress; modulates MAPK/p-65 signaling, inhibits inflammatory cytokines (IL-1β, TNF-α); alleviates inflammatory pain, improves pain behavior in models; new strategy for chronic pain.	110

Materials	Particle size(nm)	Drug Loading/Release (%)	Drug Release Characteristics	Key Biological Effects	Ref.

FA-PEG/ZIF-8	180	-	Targeted release of active substances	FA receptor-mediated targeting of activated macrophages, enhances cellular uptake; inhibits macrophage pro-inflammatory cytokine secretion, promotes anti-inflammatory factors; modulates spinal cord injury site inflammatory microenvironment, reduces glial scar formation, promotes neurological repair, improves SCI prognosis.	111
Mino@ZIF-8	-	7.9%/52.3%	Sustained release	Synergistic release of minocycline & Zn^{2+}, enhances antibacterial effect (inhibits periodontal pathogens); inhibits AKT/GSK3β/NRF2 pathway, reduces periodontal tissue oxidative damage; inhibits periodontal inflammation, reduces gingival bleeding & alveolar bone resorption, protects periodontal tissue integrity; treats periodontitis.	112
CeO2@ZIF-8 NPs	275	-	Responsive release of Ce^{3+}/Ce^{4+} & Zn^{2+}	CeO_2 exerts antioxidant effect, scavenges brain ROS, inhibits lipid peroxidation; Zn^{2+} protects neurons from apoptosis; prolongs blood circulation, efficiently crosses BBB; reduces neuronal apoptosis & brain edema after ischemic stroke reperfusion injury, improves neurological scores.	113

Materials	Particle size(nm)	Drug Loading/Release (%)	Drug Release Characteristics	Key Biological Effects	Ref.

M-ZIF-8	218	11.1%/82 %	Controlled release in GI environment	Protects aspirin from gastric acid, improves oral bioavailability; reduces GI mucosal irritation, promotes mucosal repair; Sorafenib inhibits tumor angiogenesis, synergizes with aspirin enhancing anti-inflammatory/anti-tumor effect, reduces side effects.	114
UCZN	120	10 U/mg/-20 U/mg/-	Responsive release	UOx degrades uric acid to soluble products, lowers serum uric acid; CAT clears H_2O_2 from degradation, avoids oxidative damage; blocks gout inflammation amplification pathway, reduces joint redness, swelling, heat, pain; treats gout & hyperuricemia, reduces tophi risk.	115
HLPIZ	160.8	10.8%/44.1%	NIR photothermal-responsive release	Mediates mild PTT (~42°C), regulates lipid metabolism disorder; inhibits vascular endothelial inflammation, reduces inflammatory factors; repairs damaged endothelial cells, inhibits atherosclerosis plaque formation & development, improves vascular elasticity; new strategy for cardiovascular disease.	116

Materials	Particle size(nm)	Drug Loading/Release (%)	Drug Release Characteristics	Key Biological Effects	Ref.

VanION Ps@ZIF-8	222.55± 3.15	6.37%/98. 36%	Magnetic field-targeted release (external magnetic guidance)	Magnetic field guides antibiotic targeting to prosthetic infection site, increases local concentration; efficiently clears prosthesis-related infection pathogens (including MRSA); reduces systemic dose & side effects, improves cure rate, reduces prosthesis loosening risk.	117
PDA@ZIF-8	273.4-348.4	-	Sustained release of active substances	PDA efficiently clears chronic wound ROS, reduces oxidative stress; induces macrophage M2 polarization, secretes anti-inflammatory & growth factors; promotes fibroblast proliferation, collagen deposition & angiogenesis, accelerates chronic wound healing, improves tissue quality.	118
Mn-ZIF-8	-	-	Hydrolysis releases Zn^{2+}, Mn^{2+}/Mn^{4+}	Zn^{2+} & Mn ions synergistically disrupt bacterial cell membrane, inhibit S. aureus, E. coli growth; modulates inflammation, promotes macrophage M2 polarization (increased IL-10); accelerates infected wound granulation tissue growth & re-epithelialization, shortens healing time, reduces recurrence.	119

Materials	Particle size(nm)	Drug Loading/Release (%)	Drug Release Characteristics	Key Biological Effects	Ref.

IL-4@ZIF-8@Se-Se	462	42%/92%	pH / Redox dual-responsive release (inflammatory site trigger)	L-4 targets inflammation regulation, promotes macrophage M2 polarization, inhibits IL-6, TNF-α secretion; enhances osteoblast proliferation & bone matrix synthesis; accelerates bone wound anti-inflammatory healing, reduces scar tissue, improves bone repair quality; for bone injury with inflammation.	120
R-ZnO-ZIF	70	12%/80%	pH-responsive targeted release	Specifically eradicates staphylococcal biofilms, inhibits resistant bacteria; Rifaximin targeted release to infection site, increases local concentration; reduces systemic antibiotic exposure, lowers resistance risk; efficient treatment for bacterial biofilm-related infections.	121
ZSTG	-	-/70.1%	Acidic environment-responsive release (inflammatory site)	GOx consumes glucose at inflammatory site, reduces energy supply for inflammatory cells; reduces H_2O_2 accumulation,; induces macrophage M1 to M2 conversion, promotes osteogenic microenvironment, accelerates bone repair; for inflammation-related bone defect treatment.	122

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