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# Current progress in the regulation of endogenous molecules for enhanced chemodynamic therapy

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Chemodynamic therapy (CDT) is a potential cancer treatment strategy, which relies on Fenton chemistry to transform hydrogen peroxide (H<sub>2</sub>O<sub>2</sub>) into highly cytotoxic reactive oxygen species (ROS) for tumor growth suppression. Although overproduced H<sub>2</sub>O<sub>2</sub> in cancerous tissues makes CDT a feasible and specific tumor therapeutic modality, the treatment outcomes of traditional chemodynamic agents still fall short of expectations. Reprogramming cellular metabolism is one of the hallmarks of tumors, which not only supports unrestricted proliferative demands in cancer cells, but also mediates the resistance of tumor cells against many antitumor modalities. Recent discoveries have revealed that various cellular metabolites including H<sub>2</sub>O<sub>2</sub>, iron, lactate, glutathione, and lipids have distinct effects on CDT efficiency. In this perspective, we intend to provide a comprehensive summary of how different endogenous molecules impact Fenton chemistry for a deep understanding of mechanisms underlying endogenous regulation-enhanced CDT. Moreover, we point out the current challenges and offer our outlook on the future research directions in this field. We anticipate that exploring CDT through manipulating metabolism will yield significant advancements in tumor treatment.

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## 1. Introduction

Cancer has been a severe threat to human life.<sup>1</sup> Currently, the main cancer treatments typically involve surgery, radiotherapy, and chemotherapy, yet they offer limited clinical benefits and are usually associated with serious side effects.<sup>2</sup> Therefore, there is an urgent need to explore effective and tumor-specific treatment modalities aiming to completely eradicate tumors, prevent tumor recurrence and metastasis, and improve prognosis.<sup>3,4</sup> Importantly, cancer cells show elevated reactive oxygen species (ROS) generation compared to non-cancer cells, owing to



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alterations in genetic and energy metabolism patterns.<sup>5</sup> In contrast, excessive ROS can cause irreversible oxidative cell damage, ultimately resulting in cell death.<sup>6</sup> Considering the vulnerability of cancer cells to oxidative stress, several ROS-based therapies have emerged,<sup>7</sup> including photodynamic therapy (PDT),<sup>8</sup> radiotherapy (RT),<sup>9</sup> sonodynamic therapy (SDT),<sup>10</sup> chemodynamic therapy (CDT),<sup>11,12</sup> immunotherapy, *etc.*<sup>13</sup>

CDT, an emerging efficient ROS-mediated therapeutic modality, was first given by Shi and coworkers in 2016.<sup>14</sup> It catalyzes the conversion of intracellular hydrogen peroxide (H<sub>2</sub>O<sub>2</sub>) through intratumoral Fenton or Fenton-like reactions, generating a cytotoxic hydroxyl radical (<sup>•</sup>OH), which is among the most harmful ROS.<sup>15–17</sup> This ROS generation is directly activated by endogenous chemical energy conversion without the need for exogenous stimulations (*e.g.*, laser, ultrasound, or X-rays), thus adequately overcoming the significant limitation of PDT, RT, and SDT, namely low tissue penetration depth.<sup>18–20</sup> Moreover, Fenton chemistry triggers the generation of intracellular cytotoxic radicals that are only specifically activated at tumor sites, enabling improved therapeutic effects and fewer side effects of CDT.<sup>21–23</sup> Consequently, substantial efforts have been made to engineer various Fenton reaction catalysts with amplified Fenton reaction performance for effectively treating tumors.<sup>24–27</sup>

Despite extensive attempts, the therapeutic outcome of CDT relying solely on Fenton reaction catalysts remains unsatisfactory.<sup>28</sup> The main reason is that tumor cells can construct a robust defense system that allows them to escape from ROS-induced damage by metabolic adaption, inevitably diminishing the antitumor efficacy of CDT.<sup>29–31</sup> Mounting evidence indicated that in specific biochemical contexts, aberrant metabolism of tumor cells can cause differential susceptibility of cells to CDT.<sup>32,33</sup> A detailed understanding of how endogenous metabolic pathways in tumor cells influence CDT processes is of great therapeutic interest. Herein, we first summarize the mechanisms by which H<sub>2</sub>O<sub>2</sub>, iron, lactate, glutathione (GSH), and lipid metabolism impact Fenton chemistry-mediated CDT. Then, the current state-of-the-art designs of CDT nanomedicines integrating metabolic regulation abilities for enhanced tumor therapeutic efficiency will be critically discussed. Last but not least, we discuss the representative challenges and future directions for developing CDT

agents. We expect the emergent metabolic reprogramming strategy to push forward the great process of research in the CDT field, which will benefit the clinical treatment of cancers.

## 2. Pathways controlling CDT

Considering that various endogenous molecules' metabolic processes interfere with the efficiency of Fenton-type reactions that are involved in CDT, researchers are beginning to focus on identifying the metabolic pathways that can impact therapeutic efficacies of CDT. The classifications of currently identified metabolic pathways in tumors, including H<sub>2</sub>O<sub>2</sub>, iron, lactate, GSH, and lipid metabolism, are summarized in Fig. 1.

Endogenous H<sub>2</sub>O<sub>2</sub>, as an important substrate of the Fenton reaction, can be produced from various cellular metabolic processes in cancer cells. For instance, electrons leaked from the endoplasmic reticulum stress or mitochondrial respiratory chain can be captured by molecular oxygen (O<sub>2</sub>) to form a superoxide (<sup>•</sup>O<sub>2</sub><sup>-</sup>), which is further disproportionated into H<sub>2</sub>O<sub>2</sub> by superoxide dismutase (SOD).<sup>34</sup> In addition, the production of H<sub>2</sub>O<sub>2</sub> can also be initiated by activated nicotinamide adenine dinucleotide phosphate (NADPH) oxidase (NOX) or nicotinamide adenine dinucleotide (phosphate): quinone oxidoreductase1 (NQO1).<sup>35</sup> And then, the ferrous ion (Fe<sup>2+</sup>) possesses more powerful <sup>•</sup>OH-producing ability compared to other Fenton-reactive metal ions, enabling the strategy of regulating iron metabolism attractive for achieving efficient CDT.<sup>36,37</sup> First, the extracellular transferrin (Tf)-ferric ion (Fe<sup>3+</sup>) (Tf-Fe<sup>3+</sup>) complex is carried into cells through cell surface Tf receptor protein 1 (Tfr1).<sup>38</sup> In the endosome, ferrireductase-active prostate 3 (STEAP3) mediates the transformation of Fe<sup>3+</sup> into Fe<sup>2+</sup> and divalent metal transporter 1 (DMT1) transports Fe<sup>2+</sup> to a cytosolic labile iron pool (LIP).<sup>39</sup> Excess Fe<sup>2+</sup> is excreted out of cells *via* ferroportin or is oxidized to Fe<sup>3+</sup> by the ferritin heavy chain (FHC) with ferroxidase activity to initiate subsequent Fe sequestration in ferritin, which may be limiting the Fe-driven Fenton reaction,<sup>40</sup> while iron deficiency can trigger nuclear receptor coactivator 4 (NCOA4)-dependent autophagic ferritin degradation, namely ferritinophagy, to release free iron on demand.<sup>41</sup> Lactate metabolism regulation can interfere with the construction of the acidic tumor microenvironment (TME), which provides a feasible strategy to meet the strong acidity requirements of an effective Fenton reaction.<sup>42,43</sup> Glucose is imported into cells by the glucose transporter (GLUT) on the cell membrane and subsequently transformed into pyruvate in the cytoplasm. Then lactate dehydrogenase (LDH) mediates the conversion between pyruvate and lactate, and the monocarboxylic acid transporter (MCT) mediates lactic acid efflux, inducing tumor acidification.<sup>44</sup> The cellular antioxidative system plays an indispensable role in maintaining the equilibrium of a reductive environment against excessive ROS.<sup>45</sup> Such a redox homeostasis can alleviate oxidative stress which can attack key biomacromolecules and cause irreversible cellular damage.<sup>46</sup> As the most abundant low-molecular-weight thiol-containing tripeptide synthesized in the cell cytosol, GSH has long been considered the representative reducing agent for constantly neutralizing cellular oxidative



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Fig. 1 Schematic illustration of endogenous metabolic pathways regulating Fenton chemistry-mediated CDT in tumor cells.

damage and detoxifying lipid ROS.<sup>47</sup> The high GSH content in tumor cells can weaken the effect of CDT by directly scavenging ROS.<sup>48</sup> For GSH synthesis, extracellular cystine is internalized by cells *via* the cystine/glutamate antiporter (system  $X_c^-$ ) and reduced into cysteine by thioredoxin reductase 1 (TXNRD1).<sup>49</sup> Then cysteine is conjugated with glutamate in the presence of  $\gamma$ -glutamylcystine synthetase ( $\gamma$ -GCS) to form  $\gamma$ -glutamylcystine ( $\gamma$ -glu-cys). Finally, GSH synthetase (GS) catalyzes  $\gamma$ -glutamylcystine and glycine to produce GSH. Lipid metabolism is also closely related to the effect of CDT.<sup>50</sup> Typically, acetyl-CoA is first carboxylated to form malonyl-CoA by acetyl-CoA carboxylase (ACC). Free polyunsaturated fatty acid (PUFA) generated from malonyl-CoA can be esterified by activated acyl-CoA synthetase long-chain family member 4 (ACSL4) and is inserted into the cell membrane with the assistance of lysophosphatidylcholine acyltransferase 3 (LPCAT3), eventually improving sensitivity of cells to CDT.<sup>51</sup> The above metabolic processes of endogenous molecules provide numerous practical targets for CDT treatment. Next, the mechanism of CDT regulation by each metabolic pathway will be elucidated and discussed in detail, using representative examples in the corresponding section, with the aim of providing references for designing more efficient chemodynamic agents.

## 2.1 Elevation of $H_2O_2$ contents

The  $H_2O_2$  produced by cell metabolism can be converted into lethal  $\cdot OH$  by Fenton/Fenton-like reactions.<sup>52</sup> Despite higher levels of  $H_2O_2$  in cancer cells *versus* non-cancer cells, the endogenously produced  $H_2O_2$  is still insufficient to assure a satisfactory tumor-killing effect.<sup>53</sup> Developing pertinent strategies aimed at promoting the accumulation of intracellular  $H_2O_2$  is still the primary focus of research on CDT. For example, Yang *et al.* constructed  $H_2O_2$ -responsive supramolecular polymers (PCSNs) by self-assembly of  $\beta$ -cyclodextrin-ferrocene (CD-Fc) conjugates with platinum(IV) complex modification to overcome this shortcoming (Fig. 2A).<sup>54</sup> The hydrophobic Fc in PCSNs was oxidized into water-soluble ferrocenium ( $Fc^+$ ) upon exposure to elevated  $H_2O_2$  in the tumor. The disruption of host-guest interaction in the nanostructure resulted in dissociation behavior. Meanwhile, the released platinum(IV) prodrug could be reduced into cisplatin(II) to activate NOX-mediated  $H_2O_2$  replenishment, which could further promote the Fc-initiated Fenton reaction. *In vivo* experiments confirmed that such a positive feedback loop enabling self-boosting ROS generation dramatically inhibited tumor growth. Wang and co-workers developed amphiphilic polypeptide self-assembling nanomedicine (PtkDOX-NM) for the encapsulation of  $Fe^{3+}$  and  $\beta$ -



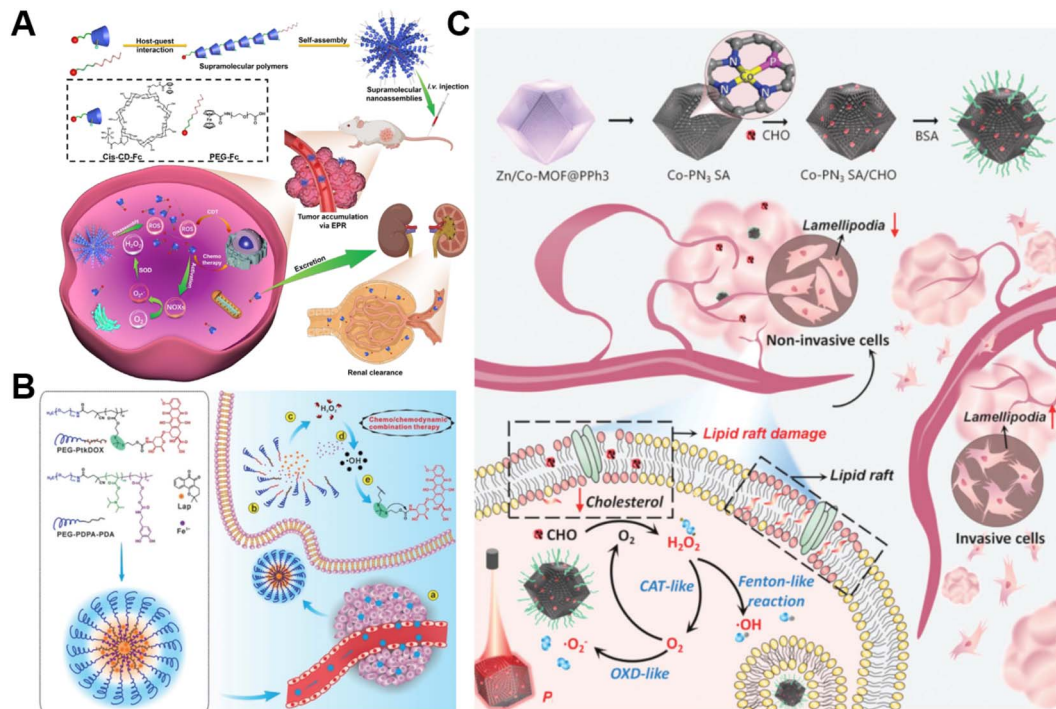


Fig. 2 (A) The main synthesis and therapeutic process of PCSNs. Reproduced with permission from ref. 54. Copyright 2021, Wiley-VCH GmbH. (B) Schemes displaying the construction process of PtkDOX-NM and its therapeutic mechanisms. Reproduced with permission from ref. 55. Copyright 2019, Wiley-VCH GmbH. (C) Illustrative diagram of the antitumor mechanism of Co-PN<sub>3</sub> SA/CHO. Reproduced with permission from ref. 59. Copyright 2023, Wiley-VCH GmbH.

lapachone (Lap), an *o*-naphthoquinone that can generate H<sub>2</sub>O<sub>2</sub> *via* futile redox cycles under the catalysis of overexpressed NQO1 (Fig. 2B).<sup>55</sup> PtkDOX-NM was formed by co-assembly of two amphiphilic polymers: poly(ethylene glycol) (PEG)-block-poly diisopropylaminoethyl methacrylate block-poly dopamine (PEG-PDPA-PDA) with pH-responsiveness and PEG-block-poly cinnamaldehyde (CA)-Fc polyprodrug (PEG-PCASFc) with ROS-responsiveness, thus achieving dual responses to pH and ROS in the TME. Next, the hydrophobic-to-hydrophilic transition of PDPA responding to the acidity of endo/lysosomes in tumor cells resulted in nanostructure disassembly and Lap release. Lap-induced H<sub>2</sub>O<sub>2</sub> generation could enhance <sup>•</sup>OH production through the Fe<sup>3+</sup>-catalyzed Fenton reaction, causing the rapid release of the DOX prodrug and the further collapse of nanostructure cleavage of the ROS-responsive thioacetal linker. Their study demonstrated that CDT combined with H<sub>2</sub>O<sub>2</sub> replenishment realizes efficient tumor inhibition with improved survival in mice.

Additionally, natural enzymes or artificial nanoenzymes have been widely applied to catalyze the transformation of intracellular substances such as glucose,<sup>56,57</sup> lactate,<sup>58</sup> and cholesterol into H<sub>2</sub>O<sub>2</sub>, which can provide an adequate substrate to accelerate the Fenton reaction. In a recent study by Lin's group, multienzyme-like Co-PN<sub>3</sub> SA/CHO nanoagents were designed and constructed by utilizing a well-dispersed phosphorus (P)-doped cobalt single atom nanozyme loaded with cholesterol oxidase (CHO) to achieve efficient tumor catalytic therapy for tumor metastasis inhibition (Fig. 2C).<sup>59</sup> The as-prepared Co-PN<sub>3</sub>

SA/CHO could concurrently mimic catalase (CAT), oxidase (OXD), and peroxidase (POD) to produce <sup>•</sup>O<sub>2</sub><sup>-</sup> and highly cytotoxic <sup>•</sup>OH for cancer cell killing. Moreover, CHO effectively catalyzed the oxidation of intratumoral cholesterol to generate H<sub>2</sub>O<sub>2</sub> and cholestenone, promoting the Co-PN<sub>3</sub> SA-mediated Fenton reaction. Simultaneously, the CHO-catalytic depletion of cholesterol resulted in the disruption of lipid raft integrity and the inhibition of invasive lamellipodium formation, suppressing tumor progression and metastasis. This work provides a promising strategy to improve therapeutic efficiency through the combination of CHO-mediated cholesterol consumption and Co-PN<sub>3</sub> SA-induced <sup>•</sup>OH generation. Notably, bacteria engineered with overexpression of respiratory chain enzyme II (NDH-2 enzyme) have also been utilized to promote intracellular H<sub>2</sub>O<sub>2</sub> content elevation. For example, Fan *et al.* designed an integrative bioreactor by assembling magnetic Fe<sub>3</sub>O<sub>4</sub> nanoparticles on the surface of NDH-2 enzyme-functionalized nonpathogenic bacterium *Escherichia coli* MG1655.<sup>60</sup> During *Escherichia coli* MG1655 respiration, NDH-2 enzyme accepted electrons from NADH and subsequently transferred electrons to O<sub>2</sub> to generate H<sub>2</sub>O<sub>2</sub>. The Fe<sub>3</sub>O<sub>4</sub> nanoparticles converted the sustainably synthesized H<sub>2</sub>O<sub>2</sub> to produce <sup>•</sup>OH through the Fenton-like reaction, achieving H<sub>2</sub>O<sub>2</sub> self-supplying CDT.

## 2.2 Disruption of iron homeostasis

The conversion of intracellular H<sub>2</sub>O<sub>2</sub> into <sup>•</sup>OH *via* Fenton chemistry is dependent on Fenton catalysts.<sup>61</sup> Fe<sup>2+</sup> and its derivatives could serve as excellent Fenton catalysts due to their



high catalytic activity in  $\cdot\text{OH}$  generation.<sup>62</sup> Generally, tumor cells require more iron ingestion compared to non-tumor cells to maintain rapid proliferation, while coordinating the regulation of iron metabolism to avoid excess iron-induced toxicity.<sup>63</sup> The regulation of intracellular iron homeostasis encompassing iron storage/release and import/export has been regarded as a promising approach for reinforcing CDT. For instance, Bu's group prepared a mesoporous silicon nanocarrier loaded with amorphous elemental  $\text{Fe}^0$  and 2-amino-1,2,4-triazole (AT, a catalase inhibitor) (DMON@ $\text{Fe}^0$ /AT) to integrate redox regulation and iron metabolism disruption for enduring CDT (Fig. 3A).<sup>64</sup> Once DMON@ $\text{Fe}^0$ /AT was endocytosed by tumor cells, acidic pH-triggered  $\text{Fe}^{2+}$  and AT release from this nanocarrier occurred. The released AT suppressed the catalase activity to promote  $\text{H}_2\text{O}_2$  accumulation and the exposed DMON-mediated GSH depletion, thus enhancing the  $\text{Fe}^{2+}$ -driven Fenton reaction. The elevated intracellular  $\cdot\text{OH}$  induced mitochondrial dysfunction, leading to the downregulation of cell membrane protein ferroportin 1 expression and the further disruption of intracellular iron homeostasis. In short, the as-prepared intelligent biodegradable DMON@ $\text{Fe}^0$ /AT demonstrates a new method for effective CDT treatment by blocking the iron exporter and regulating redox homeostasis.

Our group recently proposed a  $\text{Fe}^0$ -small interfering RNA (siRNA) composite system ( $\text{Fe}^0$ -siRNA) to realize FHC downregulation-potentiated CDT (Fig. 3B).<sup>65</sup> When the  $\text{Fe}^0$ -siRNA nanoparticles ( $\text{Fe}^0$ -siRNA NPs) were internalized into tumor cells and located in mildly acidic lysosomes, they were disassembled in the presence of  $\text{O}_2$  and released  $\text{Fe}^{2+}$  and siRNA. The acidity amplification resulting from  $\text{O}_2$  depletion could promote further degradation of  $\text{Fe}^0$ -siRNA NPs. The  $\text{Fe}^{2+}$  from  $\text{Fe}^0$ -siRNA NPs not only activated the conversion of intracellular  $\text{H}_2\text{O}_2$  into highly toxic  $\cdot\text{OH}$  for CDT, but also facilitated endosome escape of FHC siRNA through  $\cdot\text{OH}$ -triggered lipid peroxide (LPO) of endo/lysosomal membranes. More importantly, FHC silencing with siRNA suppressed the transformation of  $\text{Fe}^{2+}$  into  $\text{Fe}^{3+}$  with less Fenton activity and the sequestration of Fe in ferritin, allowing the accumulation of higher reactive  $\text{Fe}^{2+}$ , as well as increasing the CDT efficiency. In another study, Du *et al.* decorated a thiamine pyrophosphate (TPP)-etched open cavity metal-organic framework (MOF) with chitosan oligosaccharide (COS) through electrostatic interaction to develop a nanoplatfrom (termed COS@MOF) enabling hydrogen sulfide ( $\text{H}_2\text{S}$ )-activated CDT and ferroptosis for colon cancer treatment (Fig. 3C).<sup>66</sup> On the one hand, the upregulated  $\text{H}_2\text{S}$  could boost the transformation of  $\text{Fe}^{3+}$  into  $\text{Fe}^{2+}$  to improve



Fig. 3 (A) Schematic presentation of synthetic procedure of DMON@ $\text{Fe}^0$ /AT and the corresponding anticancer process. Reproduced with permission from ref. 64. Copyright 2021, Wiley-VCH GmbH. (B) Schematic description of the sequential release of  $\text{Fe}^{2+}$  and siRNA from  $\text{Fe}^0$ -siRNA NPs responding to tumor acidity for enhancement of CDT. Reproduced with permission from ref. 65. Copyright 2023, Wiley-VCH GmbH. (C) Illustration of an engineered MOF with amphiphilic ferritinophagy to cause iron ion overload for improved antitumor therapy. Reproduced with permission from ref. 66. Copyright 2023, Wiley-VCH GmbH. (D) The scheme of factors affecting endogenous labile iron-based CDT outcome of ROOR and the utilization of MLH-loading nanomedicines for CDT. Reproduced with permission from ref. 68. Copyright 2020, American Chemical Society.



Fenton reaction efficiency. On the other hand, utilization of autophagy inducer COS enabled the degradation of ferritin to promote the release of iron from ferritin and  $\text{Fe}^{2+}$  replenishment, further enhancing CDT and ROS-mediated ferroptosis. In another example, Li *et al.* developed a nanodrug (T10@cLAV) by the integration of transferrin-homing peptide T10 and cross-linked lipolic acid vesicles for  $\text{Fe}^{2+}$  self-supplying tumor therapy.<sup>67</sup> The T10@cLAV bound to the overexpressed Tf receptor on cancer cells (Tf@T10@cLAV) and was subsequently imported into endosomes/lysosomes. The acidic environment of endosomes/lysosomes could trigger the degradation of Tf, thus inducing the sustained release of iron ions and activating the Fe-driven Fenton reaction. More importantly, cLAV was disrupted with the assistance of GSH and TXNRD1 to release dihydrolipoic acid (DHLA) for DHLA-mediated reduction of  $\text{Fe}^{3+}$  to  $\text{Fe}^{2+}$ , resulting in an increase in  $\text{Fe}^{2+}$  levels to further enhance nanocatalytic therapy. Completely unlike traditional treatment strategies involving the introduction of exogenous Fenton-type metal ions, our group first utilized the intracellular labile LIP to provide the continuous catalyst for catalytic generation of toxic free radicals through Fenton-type chemistry (Fig. 3D).<sup>68</sup> We developed a pH-sensitive polymer for the co-delivery of the model ROOH molecule and LIP-increasing agent, which can sequentially respond to pH and labile iron in the TME to realize enhanced CDT.

### 2.3 Interference of lactate metabolism

In addition to the Fenton catalyst activity, the reaction conditions, particularly acidity, also influence the reaction kinetics of the Fenton reaction.<sup>69</sup> It has been confirmed that acidic pH

favors the Fenton reaction.<sup>70</sup> Lactate is considered a metabolic byproduct of glycolysis in tumor cells, leading to elevated tumor acidity.<sup>71</sup> Consequently, lactate metabolism regulation is an alternative strategy for enhancing CDT.<sup>72</sup> Shi's group reported a pH-responsive and self-augmented nanoplatform (defined as  $\text{FePt}@\text{FeO}_x@\text{TAM-PEG}$ ) fabricated by incorporating a core-shell  $\text{FePt}@\text{FeO}_x$  nanocatalyst and pH-responsive tamoxifen (TAM) drug in a poly(styrene-co-maleic anhydride) (PSMA) polymer polymeric matrix and further modifying the surface with PEG (Fig. 4A).<sup>73</sup> Once internalized by cancer cells, the nanoplatform disintegrated due to acidic pH-triggered hydrophobic-hydrophilic transitions of TAM and released the  $\text{FePt}@\text{FeO}_x$  nanocatalyst. The  $\text{FePt}@\text{FeO}_x$  nanocatalyst catalyzed the inherent  $\text{H}_2\text{O}_2$  decomposition to produce lethal  $\cdot\text{OH}$  to damage cancer cells. Meanwhile, the liberated TAM could suppress the mitochondrial complex I, thus increasing the intracellular lactate level as well as elevating environmental acidity. This simultaneously amplified  $\cdot\text{OH}$  production and accelerated disassembly of the  $\text{FePt}@\text{FeO}_x@\text{TAM-PEG}$  nanostructure, inducing more therapeutic cargo release. As a result, this intelligent nanoplatform overcomes the limitation of weak acidic conditions in tumors by introducing metabolism regulators to upregulate lactate content, thereby achieving the enhanced antitumor effect of CDT. Another related study involving the transport modulation of lactate to remodel the reaction environment is worth noting as well. Wang *et al.* prepared a calcium phosphate-based biomimetic multifunctional nanosystem with the co-delivery of a DOX- $\text{Fe}^{2+}$  complex and MCT4-inhibiting siRNA (siMCT4) ( $\text{CaP-DOX}@\text{Fe}^{2+}\text{-siMCT4-PEG-HA}$ ) for interfering lactate efflux and enhancing anti-tumor CDT (Fig. 4B).<sup>74</sup> The nanosystem was specifically taken up by tumor cells with the aid of hyaluronic

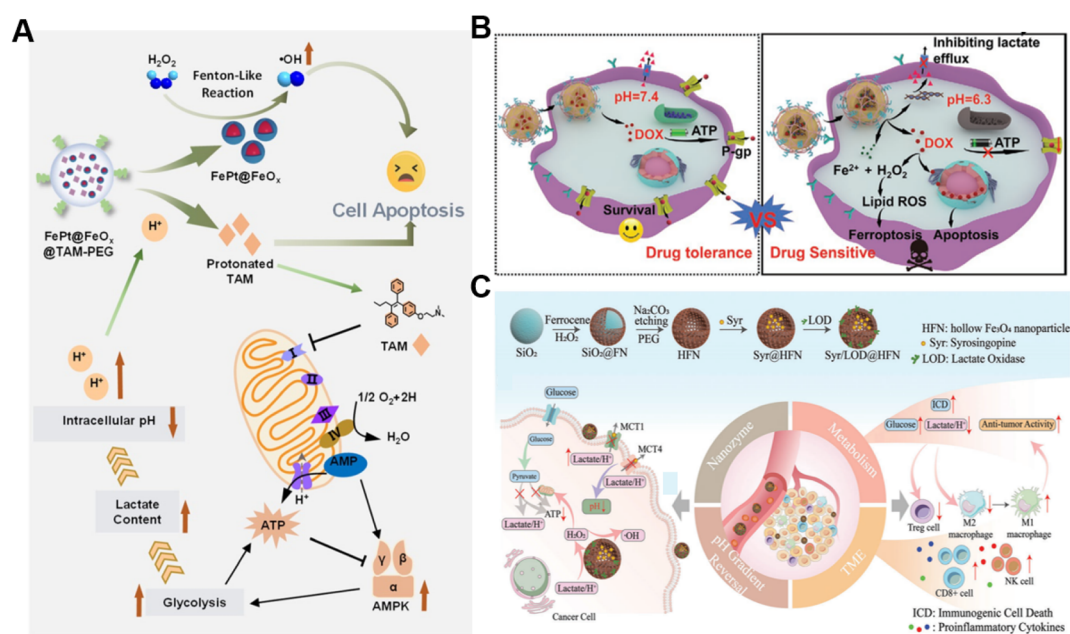


Fig. 4 (A) The underlying mechanism of enhanced CDT induced by  $\text{FePt}@\text{FeO}_x@\text{TAM-PEG}$ . Reproduced with permission from ref. 73. Copyright 2021, Wiley-VCH GmbH. (B) Schematic diagram of  $\text{CaP-DOX}@\text{Fe}^{2+}\text{-siMCT4-PEG-HA}$  enabling TME remodeling for improved CDT. Reproduced with permission from ref. 74. Copyright 2021, Wiley-VCH GmbH. (C) Illustration of the construction and application of the  $\text{Syr@LOD@HFN}$  nanoplatform. Reproduced with permission from ref. 76. Copyright 2023, Wiley-VCH GmbH.



acid (HA)-mediated targeting and degraded in the acidic environment of lysosomes due to the pH-triggered hydrolysis of CaP, resulting in the dissociation of the DOX-Fe<sup>2+</sup> complex and the release of Fe<sup>2+</sup>, DOX, and siMCT4. MCT4 silencing by siMCT4 could exacerbate intracellular acidification by blocking lactate efflux, which not only enhanced the Fe<sup>2+</sup>-driven Fenton reaction, but also decreased adenosine triphosphate (ATP) production for inhibition of DOX efflux, thus significantly improving the treatment efficiency. Typically, Wang's group developed an intelligent bioreactor (Sa@FeS) in which ferrous sulfide (FeS) nanoparticles were anchored on the surface of *Salmonella typhimurium* strain (Sa) *via* biomineralization.<sup>75</sup> The effective tumor penetration of Sa enabled FeS nanoparticles to mediate photothermally enhanced Fenton catalytic reactions in deep tumor tissues upon 1064 nm laser irradiation. At the same time, the H<sub>2</sub>S produced by Sa metabolism can facilitate glucose uptake by tumor cells, resulting in the elevation of intracellular lactic acid levels and ultimately boosting FeS-mediated CDT enhancement. Given the limited therapeutic effect of single lactate consumption, simultaneous regulation of multiple metabolic pathways may be a promising way to enhance CDT. Wu *et al.* proposed a strategy with a dual effect on lactate metabolism based on lactate oxidase

(LOX) and syrosingopine (Syr) co-loaded hollow Fe<sub>3</sub>O<sub>4</sub> nanoparticles (denoted as Syr/LOD@HFN), which could combine LOX-mediated lactate consumption and lactate transport chain blockade (Fig. 4C).<sup>76</sup> In the tumor TME, LOX could catalyze lactate to generate H<sub>2</sub>O<sub>2</sub> *in situ* while Syr-induced MCT4 down-regulation could achieve lactate metabolism blockade, leading to continuous H<sub>2</sub>O<sub>2</sub> production and pH reduction for boosting the Fe<sub>3</sub>O<sub>4</sub>-catalyzed Fenton reaction. Owing to the augmented ROS production and the reversion of the lactate-related immunosuppressive TME, this nanoplatform caused severe immunogenic cell death in tumor cells and promoted antitumor immunity. This work reveals that manipulation of multiple lactate metabolic pathways enables a better therapeutic effect than a single regulation strategy.

## 2.4 Depletion of GSH

It is well established that GSH is capable of potent ROS scavenging, thus endowing cancer cells with the ability to resist oxidative stress and weaken the effect of CDT. Generally, metals with oxidation states could consume GSH *via* undergoing redox reactions with GSH.<sup>77</sup> Our group first reported the synthesis of



Fig. 5 (A) The synthesis of CuHPT and scheme of its antitumor mechanisms against cancer cells. Reproduced with permission from ref. 79. Copyright 2022, American Chemical Society. (B) Illustration for the fabrication procedure and multifunctional application *in vivo* of MSN@MON-TPEN@PAASH nanoparticles. Reproduced with permission from ref. 82. Copyright 2019, American Chemical Society. (C) A diagram of BSO/GA-Fe(II)@liposome for enhanced CDT *via* reducing GSH biosynthesis. Reproduced with permission from ref. 84. Copyright 2021, American Chemical Society. (D) Schematic illustration of the use of the TDMH nanomedicine for multistage GSH depletion-augmented CDT. Reproduced with permission from ref. 85. Copyright 2022, American Chemical Society.



manganese dioxide (MnO<sub>2</sub>)-coated mesoporous silica nanoparticles for precise magnetic resonance imaging (MRI)-guided self-reinforcing CDT. Upon encountering the high level of GSH, MnO<sub>2</sub> NPs were degraded to release Mn<sup>2+</sup>, which not only initiated CDT by Mn<sup>2+</sup>-mediated Fenton-like chemistry but also acted as MRI contrast agents to monitor the CDT process.<sup>78</sup> Recently, redox-responsive nanosized frameworks coordinated with Cu<sup>2+</sup> and 2,3,6,7,10,11-hexahydroxytriphenylene (HPT, a catechol ligand), namely CuHPT, were designed to eliminate drug-resistant cancers by disrupting cellular redox homeostasis (Fig. 5A).<sup>79</sup> Experimental results indicated that upon being activated by GSH, CuHPT nanoparticles displayed enhanced CDT with remarkable tumor growth inhibition and negligible side effects *via* a combination of auto-oxidation and Cu<sup>+</sup>-catalyzed reactions. In addition to introducing oxidizing agents to consume GSH, numerous electrophilic reagents that can directly react with the thiol group in GSH for reduction of GSH content were utilized.<sup>80,81</sup> Guo *et al.* fabricated a hybrid mesoporous silica/organosilicate nanocomposite (MSN@MON) followed by coating the surface with disulfide bond-containing link poly(acrylic acid) and loading with *N,N,N',N'*-tetrakis(2-pyridinyl methyl)-1,2-ethanediamine (TPEN, a metal ion chelator) to obtain MSN@MON-TPEN@PAASH (Fig. 5B).<sup>82</sup> Because of GSH-induced disulfide bond cleavage in MSN@MON-TPEN@PAASH, intracellular GSH was partially consumed and the NPs collapsed to release TPEN. The liberated TPEN could chelate with Cu<sup>2+</sup> in the Cu-Zn superoxide dismutase, enabling its deactivation and the formation of a TPEN-Cu(II) complex. Then, the TPEN-Cu(II) complex was reduced into TPEN-Cu(I) by remaining GSH, inducing the further decline of antioxidant defense resulting from GSH and ultimately promoting TPEN-Cu(I)-driven Fenton-like reactions for self-reinforced CDT.

Normally, GSH biosynthesis occurs in the cytosol of almost all cells.<sup>83</sup> Blocking GSH synthesis using agents has been a good way to decrease GSH levels in cancer cells. Dong and co-workers reported a biocompatible liposomal nanoformulation containing *L*-buthionine sulfoximine (BSO) and gallic acid-ferrous ion (GA-Fe(II)) complexes to inhibit the synthesis of GSH for combined CDT-RT (Fig. 5C).<sup>84</sup> Interestingly, GA boosted the transformation of Fe<sup>3+</sup> into Fe<sup>2+</sup>, promoting the Fenton reaction to generate highly cytotoxic <sup>•</sup>OH. Besides, BSO was capable of limiting the GSH synthesis rate *via* inhibiting the activity of glutamate-cysteine ligase to reduce GSH levels, thus intensifying the Fenton reaction-enabled cancer cell damage and CDT. Moreover, Huang and co-workers developed a multi-faceted GSH depletion-potentiated CDT system (TP/2-DG@HMnO<sub>2</sub>@HA, TDMH), in which 2-deoxy-D-glucose (2-DG) and triptolide (TP) were co-encapsulated in hollow mesoporous MnO<sub>2</sub> (HMnO<sub>2</sub>) followed by modifying HA on the nanoparticles for tumor targeting (Fig. 5D).<sup>85</sup> When the nanomedicine reached the tumor area, MnO<sub>2</sub> participated in a redox reaction with GSH, yielding glutathione disulfide (GSSG) and Mn<sup>2+</sup> that could drive the Fenton-like reaction with the assistance of bicarbonate to lead to intracellular GSH consumption as well as <sup>•</sup>OH production. Meanwhile, the disintegration of the HMnO<sub>2</sub> structure occurred, triggering the release of TP and 2-DG. TP

downregulated solute carrier family 7 member 11 (SLC7A11) expression and decreased cysteine uptake, and its combination with the glycolysis inhibitor 2-DG could significantly reduce the intracellular ATP level and block the regeneration of GSH synthesis. Owing to the synergistic effect of GSH depletion and GSH synthesis inhibition, this nanoplatform efficiently strengthened CDT against tumors.

## 2.5 Regulation of lipid metabolism

The ROS accumulation induced by Fenton-type reactions can generally cause LPO. PUFAs, a family of membrane lipids possessing two or more carbon-carbon double bonds, are extremely susceptible to ROS-initiated LPO.<sup>86,87</sup> Therefore, the CDT susceptibility of cancer cells can be raised by increasing PUFA content in the lipid chain.<sup>88</sup> Taking advantage of this strategy, our group constructed a chemodynamic nanoagent (OA@Fe-SAC@EM) capable of modulating PUFA metabolism by loading oleanolic acid (OA) onto a single-atom Fe-anchored hollow carbon nanosphere (Fe-SAC) and further coating with an erythrocyte membrane (EM) for enhanced CDT (Fig. 6A).<sup>89</sup> After internalization by tumor cells, Fe-SAC could catalyze intracellular H<sub>2</sub>O<sub>2</sub> to generate <sup>•</sup>OH, which not only mediated CDT but also induced the disruption of the surface EM for the controlled release of OA. Notably, OA caused a dramatically elevated expression of ACSL4, thus increasing membrane unsaturation *via* enriched PUFAs. As a result, this nanoagent exerted enhanced chemodynamic efficiency by LPO amplification. Another relevant study was developed by Liu and co-workers. They successfully prepared the FeCo/Fe-Co dual-atom nanozyme (FeCo/Fe-Co DAzyme) possessing four-enzyme-like activities and subsequently loaded lipoxygenase (LOX) and phospholipase A2 (PLA2) into these NPs for the fabrication of a six-enzyme co-expressed nanoplatform (FeCo/Fe-Co DAzyme/PL) to enhance catalytic therapy and immunotherapy (Fig. 6B).<sup>90</sup> FeCo/Fe-Co DAzyme from this nanomedicine exhibited POD-like and OXD-like activities to catalyze both O<sub>2</sub> and H<sub>2</sub>O<sub>2</sub> to generate <sup>•</sup>O<sub>2</sub><sup>-</sup> and <sup>•</sup>OH, as well as exerted glutathione oxidase (GSHO<sub>x</sub>)-like activity for GSH elimination to reduce <sup>•</sup>OH consumption and enhanced ROS-triggered LPO. Meanwhile, FeCo/Fe-Co DAzyme also *in situ* converts H<sub>2</sub>O<sub>2</sub> into O<sub>2</sub> that could combine with free arachidonic acid (AA) liberated from PLA2-catalyzed phospholipids, producing AA-OOH through the catalysis of LOX. These two processes synergistically induced an LPO self-amplification effect for effectively initiating immunogenic ferroptosis. The resulting systemic immune activation mediated the reprogramming of ACSL4-associated phospholipids and further strengthened the cascade of immunogenic tumor ferroptosis when combined with AA. Therefore, this strategy targeting lipid metabolism provides new insight into the design of ROS-activated immunotherapy. Additionally, Yang and co-workers co-loaded Fenton catalysts hemin and lipoxidase into a pH-responsive self-assembled CaCO<sub>3</sub>-encapsulated poly(lactic-co-glycolic acid) (PLGA) nanoreactor for cascade catalytic amplification of tumor oxidative stresses.<sup>91</sup> Upon entering tumor cells, CaCO<sub>3</sub> could be degraded in the acidic





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## Notes and references

- 1 F. Bray, J. Ferlay, I. Soerjomataram, R. L. Siegel, L. A. Torre and A. Jemal, *Cancer J. Clin.*, 2018, **68**, 394–424.
- 2 P. Gotwals, S. Cameron, D. Cipolletta, V. Cremasco, A. Crystal, B. Hewes, B. Mueller, S. Quarantino, C. Sabatos-Peyton, L. Petruzzelli, J. A. Engelman and G. Dranoff, *Nat. Rev. Cancer*, 2017, **17**, 286–301.
- 3 J. Mateo, L. Steuten, P. Aftimos, F. André, M. Davies, E. Garralda, J. Geissler, D. Husereau, I. Martinez-Lopez, N. Normanno, J. S. Reis-Filho, S. Stefani, D. M. Thomas, C. B. Westphalen and E. Voest, *Nat. Med.*, 2022, **28**, 658–665.
- 4 S. H. Shin, A. M. Bode and Z. Dong, *npj Precis. Oncol.*, 2017, **1**, 12.
- 5 M. P. Murphy, H. Bayir, V. Belousov, C. J. Chang, K. J. A. Davies, M. J. Davies, T. P. Dick, T. Finkel, H. J. Forman, Y. Janssen-Heininger, D. Gems, V. E. Kagan, B. Kalyanaraman, N.-G. Larsson, G. L. Milne, T. Nyström, H. E. Poulsen, R. Radi, H. Van Remmen, P. T. Schumacker, P. J. Thornalley, S. Toyokuni, C. C. Winterbourn, H. Yin and B. Halliwell, *Nat. Metab.*, 2022, **4**, 651–662.
- 6 X. Jing, F. Yang, C. Shao, K. Wei, M. Xie, H. Shen and Y. Shu, *Mol. Cancer*, 2019, **18**, 157.
- 7 H. Pelicano, D. Carney and P. Huang, *Drug Resistance Updates*, 2004, **7**, 97–110.
- 8 E. Ju, K. Dong, Z. Chen, Z. Liu, C. Liu, Y. Huang, Z. Wang, F. Pu, J. Ren and X. Qu, *Angew. Chem., Int. Ed.*, 2016, **55**, 11467–11471.
- 9 Q. Dai, L. Wang, E. Ren, H. Chen, X. Gao, H. Cheng, Y. An, C. Chu and G. Liu, *Angew. Chem., Int. Ed.*, 2022, **61**, e202211674.
- 10 J. Fu, T. Li, Y. Zhu and Y. Hao, *Adv. Funct. Mater.*, 2019, **29**, 1906195.
- 11 X. Niu, Y. Zhu, C. Ding, J. Ma, P. Wei, Y. Lin, W. Fang, Q. He, C. Li, J. Cheng, J. Zou, L. Lin, X. Chen and D. Kang, *Adv. Funct. Mater.*, 2023, **33**, 2306778.
- 12 L.-S. Lin, T. Huang, J. Song, X.-Y. Ou, Z. Wang, H. Deng, R. Tian, Y. Liu, J.-F. Wang, Y. Liu, G. Yu, Z. Zhou, S. Wang, G. Niu, H.-H. Yang and X. Chen, *J. Am. Chem. Soc.*, 2019, **141**, 9937–9945.
- 13 B. Guo, F. Yang, L. Zhang, Q. Zhao, W. Wang, L. Yin, D. Chen, M. Wang, S. Han, H. Xiao and N. Xing, *Adv. Mater.*, 2023, **35**, e2212267.
- 14 C. Zhang, W. Bu, D. Ni, S. Zhang, Q. Li, Z. Yao, J. Zhang, H. Yao, Z. Wang and J. Shi, *Angew. Chem., Int. Ed.*, 2016, **55**, 2101–2106.
- 15 R. Zhao, Y. Zhu, L. Feng, B. Liu, Y. Hu, H. Zhu, Z. Zhao, H. Ding, S. Gai and P. Yang, *Adv. Mater.*, 2024, **36**, e2307115.
- 16 M. Yu, Z. Ye, S. Liu, Y. Zhu, X. Niu, J. Wang, R. Ao, H. Huang, H. Cai, Y. Liu, X. Chen and L. Lin, *Angew. Chem., Int. Ed.*, 2024, **63**, e202318155.
- 17 T. Chen, P. Hou, Y. Zhang, R. Ao, L. Su, Y. Jiang, Y. Zhang, H. Cai, J. Wang, Q. Chen, J. Song, L. Lin, H. Yang and X. Chen, *Angew. Chem., Int. Ed.*, 2021, **60**, 15006–15012.
- 18 Z. Tang, Y. Liu, M. He and W. Bu, *Angew. Chem., Int. Ed.*, 2019, **58**, 946–956.
- 19 Y. Zhou, S. Fan, L. Feng, X. Huang and X. Chen, *Adv. Mater.*, 2021, **33**, e2104223.
- 20 X. Wang, X. Zhong, Z. Liu and L. Cheng, *Nano Today*, 2020, **35**, 100946.
- 21 S. L. Li, P. Jiang, F. L. Jiang and Y. Liu, *Adv. Funct. Mater.*, 2021, **31**, 2100243.
- 22 C. Cao, X. Wang, N. Yang, X. Song and X. Dong, *Chem. Sci.*, 2022, **13**, 863–889.
- 23 Y. Wu, Y. Li, G. Lv and W. Bu, *Chem. Sci.*, 2022, **13**, 2202–2217.
- 24 T. Chen, Z. Chen, Q. Zhou, H. Ding, P. Gong, J. Wang, H. Cai, R. Ao, M. Yu, J. Song, L. Lin and H. Yang, *Adv. Funct. Mater.*, 2022, **32**, 2208720.
- 25 Q. Tian, F. Xue, Y. Wang, Y. Cheng, L. An, S. Yang, X. Chen and G. Huang, *Nano Today*, 2021, **39**, 101162.
- 26 D. Jana and Y. Zhao, *Explore*, 2022, **2**, 20210238.
- 27 Y. Zhu, W. Wang, P. Gong, Y. Zhao, Y. Pan, J. Zou, R. Ao, J. Wang, H. Cai, H. Huang, M. Yu, H. Wang, L. Lin, X. Chen and Y. Wu, *ACS Nano*, 2023, **17**, 3064–3076.
- 28 S. Zhang, L. Jin, J. Liu, Y. Wang, T. Zhang, Y. Liu, Y. Zhao, N. Yin, R. Niu, D. Xue, Y. Yu and Y. Yang, *Adv. Funct. Mater.*, 2022, **32**, 2113397.
- 29 P. Icard and H. Lincet, *Biochim. Biophys. Acta*, 2012, **1826**, 423–433.
- 30 L. K. Borroughs and R. J. DeBerardinis, *Nat. Cell Biol.*, 2015, **17**, 351–359.
- 31 R. A. Cairns, I. S. Harris and T. W. Mak, *Nat. Rev. Cancer*, 2011, **11**, 85–95.
- 32 J. Yang, Y. Zhao, Y. Zhou, X. Wei, H. Wang, N. Si, J. Yang, Q. Zhao, B. Bian and H. Zhao, *Biomaterials*, 2022, **286**, 121565.
- 33 F. Gao, J.-H. Dong, C. Xue, X.-X. Lu, Y. Cai, Z.-Y. Tang and C.-J. Ou, *Small*, 2024, 2310248.
- 34 H. Wu, Y. Wang, M. Ying, C. Jin, J. Li and X. Hu, *Signal Transduct. Target Ther.*, 2021, **6**, 242.
- 35 P. A. Ma, H. Xiao, C. Yu, J. Liu, Z. Cheng, H. Song, X. Zhang, C. Li, J. Wang, Z. Gu and J. Lin, *Nano Lett.*, 2017, **17**, 928–937.
- 36 X. R. Xu, H. B. Li, W. H. Wang and J. D. Gu, *Chemosphere*, 2004, **57**, 595–600.
- 37 J. Wang and K. Pantopoulos, *Biochem. J.*, 2011, **434**, 365–381.
- 38 J. Zheng and M. Conrad, *Cell Metab.*, 2020, **32**, 920–937.
- 39 Y. Xie, W. Hou, X. Song, Y. Yu, J. Huang, X. Sun, R. Kang and D. Tang, *Cell Death Differ.*, 2016, **23**, 369–379.
- 40 C. Liang, X. Zhang, M. Yang and X. Dong, *Adv. Mater.*, 2019, **31**, e1904197.
- 41 B. R. Stockwell, J. P. Friedmann Angeli, H. Bayir, A. I. Bush, M. Conrad, S. J. Dixon, S. Fulda, S. Gascon, S. K. Hatzios, V. E. Kagan, K. Noel, X. Jiang, A. Linkermann, M. E. Murphy, M. Overholtzer, A. Oyagi, G. C. Pagnussat,



- J. Park, Q. Ran, C. S. Rosenfeld, K. Salnikow, D. Tang, F. M. Torti, S. V. Torti, S. Toyokuni, K. A. Woerpel and D. D. Zhang, *Cell*, 2017, **171**, 273–285.
- 42 X. Chen, H. Zhang, M. Zhang, P. Zhao, R. Song, T. Gong, Y. Liu, X. He, K. Zhao and W. Bu, *Adv. Funct. Mater.*, 2020, **30**, 1908365.
- 43 C. S. Hong, N. A. Graham, W. Gu, C. Espindola Camacho, V. Mah, E. L. Maresh, M. Alavi, L. Bagryanova, P. A. L. Krotee, B. K. Gardner, I. S. Behbahan, S. Horvath, D. Chia, I. K. Mellinshoff, S. A. Hurvitz, S. M. Dubinett, S. E. Critchlow, S. K. Kurdistani, L. Goodglick, D. Braas, T. G. Graeber and H. R. Christofk, *Cell Rep.*, 2016, **14**, 1590–1601.
- 44 J. Gu, J. Sun, Y. Liu, G. Chong, Y. Li and H. Dong, *Nano Res.*, 2022, **16**, 654–671.
- 45 T. Liu, L. Sun, Y. Zhang, Y. Wang and J. Zheng, *J. Biochem. Mol. Toxicol.*, 2022, **36**, e22942.
- 46 D. Trachootham, J. Alexandre and P. Huang, *Nat. Rev. Drug Discovery*, 2009, **8**, 579–591.
- 47 G. Wu, J. R. Lupton, N. D. Turner, Y.-Z. Fang and S. Yang, *J. Nutr.*, 2004, **134**, 489–492.
- 48 A. Bansal and M. C. Simon, *J. Cell Biol.*, 2018, **217**, 2291–2298.
- 49 B. Niu, K. Liao, Y. Zhou, T. Wen, G. Quan, X. Pan and C. Wu, *Biomaterials*, 2021, **277**, 121110.
- 50 L. E. Pope and S. J. Dixon, *Trends Cell Biol.*, 2023, **33**, 1077–1087.
- 51 Y. Zou, W. S. Henry, E. L. Ricq, E. T. Graham, V. V. Phadnis, P. Maretich, S. Paradkar, N. Boehnke, A. A. Deik, F. Reinhardt, J. K. Eaton, B. Ferguson, W. Wang, J. Fairman, H. R. Keys, V. Dančík, C. B. Clish, P. A. Clemons, P. T. Hammond, L. A. Boyer, R. A. Weinberg and S. L. Schreiber, *Nature*, 2020, **585**, 603–608.
- 52 W. Xuan, Y. Xia, T. Li, L. Wang, Y. Liu and W. Tan, *J. Am. Chem. Soc.*, 2020, **142**, 937–944.
- 53 P. Yu, X. Li, G. Cheng, X. Zhang, D. Wu, J. Chang and S. Wang, *Chin. Chem. Lett.*, 2021, **32**, 2127–2138.
- 54 K. Yang, G. Yu, Z. Yang, L. Yue, X. Zhang, C. Sun, J. Wei, L. Rao, X. Chen and R. Wang, *Angew. Chem., Int. Ed.*, 2021, **60**, 17570–17578.
- 55 S. Wang, G. Yu, Z. Wang, O. Jacobson, L. S. Lin, W. Yang, H. Deng, Z. He, Y. Liu, Z. Y. Chen and X. Chen, *Angew. Chem., Int. Ed.*, 2019, **58**, 14758–14763.
- 56 C. Fang, Z. Deng, G. Cao, Q. Chu, Y. Wu, X. Li, X. Peng and G. Han, *Adv. Funct. Mater.*, 2020, **30**, 1910085.
- 57 Y. Ding, H. Xu, C. Xu, Z. Tong, S. Zhang, Y. Bai, Y. Chen, Q. Xu, L. Zhou, H. Ding, Z. Sun, S. Yan, Z. Mao and W. Wang, *Adv. Sci.*, 2020, **7**, 2001060.
- 58 T. J. Zhou, X. Wan, M. M. Zhang, D. M. Liu, L. L. Huang, L. Xing, Y. Wang and H. L. Jiang, *Biomaterials*, 2023, **300**, 122205.
- 59 Y. Liu, R. Niu, R. Deng, Y. Wang, S. Song and H. Zhang, *Adv. Mater.*, 2024, **36**, e2307752.
- 60 J.-X. Fan, M.-Y. Peng, H. Wang, H.-R. Zheng, Z.-L. Liu, C.-X. Li, X.-N. Wang, X.-H. Liu, S.-X. Cheng and X.-Z. Zhang, *Adv. Mater.*, 2019, **31**, 1808278.
- 61 W. Li, Y. Wang and A. Irini, *Chem. Eng. J.*, 2014, **244**, 1–8.
- 62 R. Yang, Z. Ouyang, H. Guo, J. Qu, J. Xia, M. Shen and X. Shi, *Nano Today*, 2022, **46**, 101615.
- 63 L. M. Bystrom, M. L. Guzman and S. Rivella, *Antioxid. Redox Signal.*, 2012, **20**, 1917–1924.
- 64 Y. Liu, S. Zhai, X. Jiang, Y. Liu, K. Wang, C. Wang, M. Zhang, X. Liu and W. Bu, *Adv. Funct. Mater.*, 2021, **31**, 2010390.
- 65 J. Wang, H. Ding, Y. Zhu, Y. Liu, M. Yu, H. Cai, R. Ao, H. Huang, P. Gong, Y. Liao, Z. Chen, L. Lin, X. Chen and H. Yang, *Angew. Chem., Int. Ed.*, 2023, **62**, e202302255.
- 66 J. Du, M. Zhou, Q. Chen, Y. Tao, J. Ren, Y. Zhang and H. Qin, *Adv. Funct. Mater.*, 2023, **33**, 2215244.
- 67 S. Zhang, X. Wu, X. Liao and S. Zhang, *J. Am. Chem. Soc.*, 2024, **146**, 8567–8575.
- 68 L. Lin, S. Wang, H. Deng, W. Yang, L. Rao, R. Tian, Y. Liu, G. Yu, Z. Zhou, J. Song, H.-H. Yang, Z.-Y. Chen and X. Chen, *J. Am. Chem. Soc.*, 2020, **142**, 15320–15330.
- 69 S. Fu, R. Yang, L. Zhang, W. Liu, G. Du, Y. Cao, Z. Xu, H. Cui, Y. Kang and P. Xue, *Biomaterials*, 2020, **257**, 120279.
- 70 Y. Liu, X. Ji, W. W. L. Tong, D. Askhatova, T. Yang, H. Cheng, Y. Wang and J. Shi, *Angew. Chem., Int. Ed.*, 2018, **57**, 1510–1513.
- 71 Q. Cheng, X.-L. Shi, Q.-L. Li, L. Wang and Z. Wang, *Adv. Sci.*, 2024, **11**, 2305662.
- 72 F. Tian, S. Wang, K. Shi, X. Zhong, Y. Gu, Y. Fan, Y. Zhang and M. Yang, *Adv. Sci.*, 2021, **8**, e2102595.
- 73 L. Shi, Y. Wang, C. Zhang, Y. Zhao, C. Lu, B. Yin, Y. Yang, X. Gong, L. Teng, Y. Liu, X. Zhang and G. Song, *Angew. Chem., Int. Ed.*, 2021, **60**, 9562–9572.
- 74 X. Wang, Y. Zhao, Y. Hu, Y. Fei, Y. Zhao, C. Xue, K. Cai, M. Li and Z. Luo, *Small*, 2021, **17**, e2102269.
- 75 W. Wang, J. Song, W. Yu, M. Chen, G. Li, J. Chen, L. Chen, L. Yu and Y. Chen, *Adv. Funct. Mater.*, 2024, 2400929.
- 76 S. Wu, L. Xu, C. He, P. Wang, J. Qin, F. Guo and Y. Wang, *Adv. Sci.*, 2023, **10**, e2300686.
- 77 J. Lu, Z. Jiang, J. Ren, W. Zhang, P. Li, Z. Chen, W. Zhang, H. Wang and B. Tang, *Angew. Chem., Int. Ed.*, 2022, **61**, e202114373.
- 78 L. S. Lin, J. Song, L. Song, K. Ke, Y. Liu, Z. Zhou, Z. Shen, J. Li, Z. Yang, W. Tang, G. Niu, H. H. Yang and X. Chen, *Angew. Chem., Int. Ed.*, 2018, **57**, 4902–4906.
- 79 J. Liu, Y. Yuan, Y. Cheng, D. Fu, Z. Chen, Y. Wang, L. Zhang, C. Yao, L. Shi, M. Li, C. Zhou, M. Zou, G. Wang, L. Wang and Z. Wang, *J. Am. Chem. Soc.*, 2022, **144**, 4799–4809.
- 80 J. R. Winther and C. Thorpe, *Biochim. Biophys. Acta*, 2014, **1840**, 838–846.
- 81 Y. Li, P. Zhao, T. Gong, H. Wang, X. Jiang, H. Cheng, Y. Liu, Y. Wu and W. Bu, *Angew. Chem., Int. Ed.*, 2020, **59**, 22537–22543.
- 82 Y. Guo, Y. Xu, Q. Bao, C. Shen, D. Ni, P. Hu and J. Shi, *ACS Nano*, 2021, **15**, 16286–16297.
- 83 H. J. Forman, H. Zhang and A. Rinna, *Mol. Aspects Med.*, 2009, **30**, 1–12.
- 84 Z. Dong, L. Feng, Y. Chao, Y. Hao, M. Chen, F. Gong, X. Han, R. Zhang, L. Cheng and Z. Liu, *Nano Lett.*, 2019, **19**, 805–815.
- 85 Y. Huang, S. Wu, L. Zhang, Q. Deng, J. Ren and X. Qu, *ACS Nano*, 2022, **16**, 4228–4238.



- 86 L. Magtanong, P. J. Ko and S. J. Dixon, *Cell Death Differ.*, 2016, **23**, 1099–1109.
- 87 J. Luo, Y. Li, Y. Li, X. Chen, P. Du, Z. Wang, A. Tian and Y. Zhao, *ACS Nano*, 2023, **17**, 25257–25268.
- 88 K. D'Herde and D. V. Krysko, *Nat. Chem. Biol.*, 2017, **13**, 4–5.
- 89 Y. Zhu, P. Gong, J. Wang, J. Cheng, W. Wang, H. Cai, R. Ao, H. Huang, M. Yu, L. Lin and X. Chen, *Angew. Chem., Int. Ed.*, 2023, **62**, e202218407.
- 90 Y. Liu, R. Niu, R. Deng, S. Song, Y. Wang and H. Zhang, *J. Am. Chem. Soc.*, 2023, **145**, 8965–8978.
- 91 Z. Yang, Y. Zhu, Z. Dong, W. Li, N. Yang, X. Wang, L. Feng and Z. Liu, *Nat. Commun.*, 2021, **12**, 4299.

