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Thorpe, Thomas, Marshall, James, Harawa, Vanessa et al. (12 more authors) (2022) Multifunctional biocatalyst for conjugate reduction and reductive amination. Nature. pp. 86-91. ISSN 0028-0836

https://doi.org/10.1038/s41586-022-04458-x

Multifunctional biocatalyst for conjugate reduction and reductive amination

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Summary

Chiral amine diastereomers are ubiquitous in pharmaceuticals and agrochemicals,[1] yet their preparation often relies on low-efficiency multi-step synthesis.[2] These valuable compounds must be manufactured asymmetrically, as their biochemical properties can differ based on the chirality of the molecule. Herein, we report the discovery and characterisation of a multi-functional biocatalyst for amine synthesis, which operates using a previously unreported mechanism. This enzyme (EneIRED), identified within a metagenomic imine reductase (IRED) collection[3] and originating from an unclassified *Pseudomonas* species, possesses an unusual active site architecture that facilitates amine-activated conjugate alkene reduction followed by reductive amination. This enzyme can couple a broad selection of *α,β*-unsaturated carbonyls with amines for the efficient preparation of chiral amine diastereomers baring up to three stereocentres. Mechanistic and structural studies have been carried out to delineate the order of individual steps catalysed by EneIRED which have led to a proposal for the overall catalytic cycle. This work shows that the IRED family can serve as a platform for facilitating the discovery of further enzymatic activities for application in synthetic biology and organic synthesis.

Main

Reductive amination (RA) is one of the most widely used and powerful methodologies in medicinal chemistry for the synthesis of high value chiral amines,[1] enabling efficient formation of C-N bonds through the reductive coupling of carbonyls and amines.[2,4] The development of effective catalysts for asymmetric RA continues to be explored, including those based on metallo-,[5,6] organo-[7] and biocatalysis.[3,8–10] Furthermore, valuable amino-containing compounds often contain multiple stereogenic centres (Fig. 1a), however total control of their chirality is more

challenging, resulting in less efficient multistep syntheses[11] or more complex tandem catalysis systems.[12,13] Whilst multi-enzyme systems are highly amenable to these biomimetic tandem processes (Fig. 1b), difficulties in their assembly arise from incompatibilities of their reaction medium and reaction rates, which can lead to by-product formation and intricate reaction setup.[14] To address these issues and achieve the desired reaction metrics, significant protein engineering is often required on each enzyme component.[15] Discovery of a single enzyme that can control multiple stereocentres through a RA-like process would be highly desirable and enable efficient synthesis of valuable amine diastereomers using a one-pot, one-catalyst system (Fig. 1c).

Nicotinamide-dependent enzymes are versatile biocatalysts for both asymmetric conjugate reduction (CR)[16,17] and reductive amination (RA).[8,9,18,19] For RA, imine reductases (IREDs) have emerged as attractive catalysts since they possess broad substrate scope and can be engineered for industrial application.[20,21] IREDs are characterised as chemoselective for the reduction of C=N bonds[22–24] although under exceptional circumstances they can reduce C=O bonds of activated carbonyl species.[25] Furthermore, we recently demonstrated that IREDs could be combined with ene-reductases (EREDs) in a one-pot process to reduce both the C=C and C=N bonds of cyclic α,β-unsaturated imines (ene-imines).[26] We speculated that if an IRED could catalyse both of these steps, in a similar fashion to recently reported biosynthetic oxidoreductases,[27,28] this biocatalyst could be applied to the CR-RA of α,β-unsaturated carbonyls and allow access to enantioenriched amine diastereomers (Fig. 1c).

In pursuit of this activity, we screened both reported[8,24,29–31] and our recently established (meta)genomic IREDs[3,32] for the complete reduction of cyclic ene-imine **I** to amine **II** (Fig. 1d and Supplementary Table ST1). Amongst the 389 IREDs screened, we observed that 262 catalysed reduction of **I**, with the majority behaving conventionally, *i.e.* reducing the C=N bond only (206 enzymes, 53%). A smaller subset of IREDs were able to catalyse the reduction of both the C=C and C=N bonds of **I** to the diastereomerically enriched product **II** (44 enzymes, 11%). Furthermore, in a complementary fashion, some IREDs reduced solely the C=C bond (12 enzymes, 3%). Mapping the reaction profiles against genetic sequence indicated localised sequence**-**activity correlation only (Extended Data Fig. ED1). One metagenomic enzyme, likely originating from an unclassified *Pseudomonas* species (EneIRED, Fig. 1d, see Supplementary Fig. SF2 for predicted operon of EneIRED), exhibited excellent full reduction of **I** to **II**, and hence this enzyme was selected for further study.

EneIRED was examined for the ability to catalyse CR-RA of cyclohex-2-enone **1** with allylamine **a**, monitoring for potential reduced and coupled products **1a**, **1'**, **1'a** including aza-conjugate addition. The reaction proceeded with high conversion, forming predominately CR-RA product **1'a** and CR product **1'** without concomitant generation of direct RA product **1a**. Optimisation of the buffer type, pH as well as co-solvent (Extended Data Fig. ED2) increased the

conversion to **1'a** with 1.1 eq. of allylamine (61%, Supplemental Table ST2) and could be scaled-up using 20 eq. of **a** yielding the hydrochloride salt in 69% yield (Fig. 1e).

We explored the substrate scope of EneIRED using the optimised reaction conditions (Fig. 2, for a full list of substrates see Supplementary Fig. SF4). EneIRED exhibited a broad substrate scope yielding CR and mono-RA products. Generally, unhindered enals and enones could be transformed with high chemoselectivity to the corresponding saturated amines. This trend is observed by comparing the reaction profiles of increasingly hindered C_2-substituted but-2-enals **3**-**5** or decreasingly hindered amine donors **a**-**c** with cinnamaldehyde **6.**

Cyclic enones with various ring sizes were all accepted by EneIRED, with 6- and 5-membered, **1** and **10,** affording good conversion to the corresponding saturated amine products **1'b** or **10'b** without direct RA products **1b** or **10b**. 2-, 3- and 4,4'-methyl substituted cycloalkyl-2-enones **12-15** were also accepted by the enzyme, with 3-substituted **12** and **15** offering high conversion, chemo- and stereoselectivity to the corresponding CR-RA products **12'b** and **15'b**. C-3-substitution of the cyclohex-2-enone scaffold **15**-**22** was generally well tolerated, offering excellent conversion, chemo-, enantio- and (*trans*)-diastereoselectivity to the corresponding *N*-substituted cyclohexylamines **15'b, 16'b, 18'b** and **20'b**. Factors controlling stereochemistry at C-2 of the α,β-unsaturated carbonyl are discussed in the Supplementary Information (9.2).

A broad selection of amine partners was explored using 3-methyl-cyclohexenone **15** as substrate partner. Excellent conversion, chemo-, enantio- and diastereoselectivities were observed for small linear primary amines **a**-**c**, **e-h**. Notably, functionalised products from amines **a**, **e**, **g**, **h** could be formed efficiently as well as the secondary amine pyrrolidine **i**.

We were also keen to see if CR-RA products with additional stereocentres could be synthesised. (*R*)- or (*S*)-3-fluoropyrrolidine **j** could be coupled efficiently with 3-methylcyclohexenone **15**, affording (*cis*)**-15'j** with high chemo- and diastereoselectivity (see Supplementary Discussion for details on the use of *rac*-**j**). Furthermore, CR-RA of cyclopropylamine **b** with racemic enone **23** demonstrated that the single catalyst could control three stereocentres on cyclohexylamine ring **23'b**, offering excellent enantioselectivity as well as good chemo- and diastereoselectivity.

To assess the synthetic applicability of the EneIRED-catalysed CR-RA, preparative-scale syntheses were performed using **15** partnered with **a**, **b** or **i** as well as **16** combined with **b** forming **15'a**, **15'b**, **15'i**, and **16'b** as the hydrochloride salts in 81%, 77%, 60% and 72% isolated yield respectively (Extended Data Fig. ED3). The former example could be intensified to 50 mM enone **15** and 250 mM (5 eq.) amine **b** substrate loadings, affording **15'b** in 64% isolated yield at a scale of 1.0 mmol (110 mg, TTN = 640).

We next carried out mechanistic investigations to further characterise EneIRED and identify any intermediates formed during CR-RA. EneIRED effectively catalysed the reaction using NADPH (2 eq.) only. Furthermore in the absence of EneIRED or the nicotinamide cosubstrate regeneration system, no reduction products could be detected (Extended Data Fig. ED4a-c). Isotopic labelling experiments, using the *in situ* generated deuterated nicotinamide cosubstrate from D-glucose-1-d_1, yielded 1,3-d_2-**15'b** from **15** and **b** as the hydrochloride salt confirming hydride transfer occurs at C-1 and C-3 of the unsaturated carbonyl substrate (Fig. 3a, 75% isolated yield, 91% 2D incorporation, see Supplementary Fig. SF4 and SF5 for further details).

A time course study is consistent with a stepwise CR-RA double hydride transfer mechanism, in which firstly enone **15** undergoes CR to an intermediate enantioenriched ketone (*R*)-**15'**, before RA of the intermediate to the final product (1*R*,3*R*)-**15'b** (Extended Data Fig. ED5a). Importantly, no direct RA product **15b**, a potential alternative intermediate**,** was observed during the time course, suggesting that the reaction proceeds via ketone **15'** only. Furthermore, whilst **15b** was inert to redox activity with EneIRED and co-substrates, ketone (*R*)-**15'** undergoes RA with **b** (Extended Data Fig. ED4d-e), indicating **15**' as the sole reaction intermediate.

We were also keen to probe the enzyme-substrate complex formed during the CR step. Omitting any amine donor from the reaction yielded no product of either CR or RA (Fig. 3b), suggesting that the IRED-catalysed reaction explicitly requires the presence of an amine in the catalytic cycle. Furthermore, no activity was observed when combining either enone **15** with tertiary amine donor triethylamine **k** or unsaturated ester methyl cyclohex-1-ene-1-carboxylate and cyclopropylamine **b**, suggesting that EneIRED-catalysed CR likely occurs *via* an ene-imine-NAD(P)H-biocatalyst complex, reminiscent of organocatalytic CR systems[33] that have recently been hosted in an artificial enzyme.[34] To the best of our knowledge this is the first example of an enzyme that achieves CR by this type of ene-imine intermediate.

The multiple activities of EneIRED prompted us to study its structure using X-ray crystallography. Crystals of EneIRED in complex with $NADP^+$ were obtained in the $P2_1$ space group with two molecules in the asymmetric unit, forming the now familiar domain swapping dimeric fold observed in for the IRED family (Fig. 3c).[8,35] A comparison of the monomer structure with others in the Protein DataBank using the DALI server[36] revealed that the closest existing IRED structures in the database were those from *Streptosporangium roseum* (PDB code 5OCM; 30% seq id; rmsd 1.6 Å over 286 Ca atoms),[37] *Aspergillus oryzae* (5G6S; 30%; 1.6 Å)[8] and *Stackebrandtia nassauensis* (6JIT, 30%; 2.0 Å). The most striking differences with other IRED folds having structures in the database were observed in the active site (Fig. 3f, see Extended Data Fig. ED6 for electron density).

EneIRED possesses a tyrosine residue, Y177, at the top of the ceiling of the active site as drawn, in common with other IREDs, such as those from *Streptomyces* sp. GF3546 (4OQY),[38] *Bacillus cereus* (4D3F),[39] and *Nocardopsis halophila* (4D3S),[38] which have been shown to display (*S*)-stereoselectivity for the reduction of model imine compound 2-methyl pyrroline. In common with those enzymes, Y177 forms a hydrogen bond with the hydroxyl group of a side-chain, in this case threonine T101, which in turn H-bonds to the 2'-hydroxyl of the ribose in $NADP^+$. However, EneIRED also possesses an additional tyrosine residue Y181 that also points into the active site towards the cosubstrate binding cleft, which is a hydrophobic leucine in both 5OCM and 6JIT. The active site also features a number of cyclic and hydrophobic amino acid side-chains F185, Y269, H245 and A240 with Y129 at the rear and V244 at the front, that form a closed cavity which has been previously observed to be suitable for binding, especially of planar cyclic imines in IRED structures.[8,40]

We explored the role of Y177 and Y181 in CR-RA through the creation of point variants of EneIRED. Point mutation of Y181 (EneIRED-Y181A/L/F) gave mutants that exhibited lower stereoselectivity for CR-RA of **15** with **b** correspondent with the volume of the residue (Fig. 3e), suggesting that this position is important in providing a steric constraint for controlling the face for hydride delivery in both CR and RA steps. Both EneIRED-Y181A and the point mutation of Y177, EneIRED-Y177A, exhibited significant reduction in the rate of CR-RA compared to the wild-type, *i.e.* a lower rate of the consumption of **15** and accumulation of **15'b** (Extended Data Fig. ED5b-c). Interestingly, for Y177A, only low levels of ketone (< 5%) were observed during the course of the reaction suggesting that this residue is important for CR and not RA.

A model of the enzyme active site in complex with the ene-imine formed by condensation of **15** with **b** was constructed using AutoDock Vina (Fig. 3f).[41] In the top pose, the model suggests that the closest atom to the C-4 of the pyridinium ring of the cosubstrate, suitable for acceptance of a hydride, is the prochiral carbon atom of the C=C bond. Delivery of a hydride to this atom as shown in the model would give the experimentally observed (*R*)-configuration at this centre.

Based on our structural and mechanistic investigation the following dual EneIRED catalytic cycle is proposed for productive CR-RA (Fig. 4a). First, the nicotinamide cosubstrate and condensation product of *α,β*-unsaturated carbonyl **V** and amine form an active-site ene-imine-NAD(P)H- EneIRED complex **VI**. Where substrate orientation kinetically favours the C-3 of the ene-imine orientated toward the nicotinamide hydride, CR yields the stereoenriched 1-enamine-$NAD(P)^+$- EneIRED complex **VII**. Following this, the oxidised cosubstrate and prochiral 1-enamine are expelled from the enzyme, with the latter being hydrolysed in solution to form the stereoenriched carbonyl **VIII**. A further NAD(P)H cosubstrate binds to the enzyme together with the condensation product of the previously released carbonyl **VIII** and

amine to form complex **IX** which undergoes the expected IRED-catalysed RA,[9] yielding the stereoenriched final product **X**.

Finally, we sought to further extend the enzyme catalysed CR-RA by employing a conjugated dienyl-ketone. Whilst **24** was susceptible to aza-conjugate addition, EneIRED-catalysed 4- and 6-electron CR-RA of *α*,*β*,*γ*,*δ*-unsaturated enone **24** in combination with cyclopropylamine **b**, affording **24'b** and (*trans*)-**24"b=16'b** respectively (Fig. 4b). Interestingly, 6-electron CR-RA product **24"b=16'b** possessed analogous diastereo- and enantioselectivity to the CR-RA of the corresponding ethyl substituted *α*,*β*-unsaturated enone **16**, suggesting that reduction of **24** proceeds by a similar pathway to that of **16**. This experiment suggests that EneIRED could be used to establish additional stereogenic centres during the CR-RA process.

In summary, we report the discovery and characterisation of a multifunctional biocatalyst (EneIRED) that is able to catalyse CR as well as imine reduction and RA. EneIRED possesses broad substrate scope allowing for the stereoselective preparation of valuable amine diastereomers in a one-pot, one-catalyst reaction starting from simple prochiral starting materials. Mechanistic and structural studies reveal a multi-step process in which EneIRED first catalyses amine-activated CR of *α*,*β*-unsaturated carbonyl *via* a previously undescribed ene-imine-NAD(P)H-enzyme complex. We envisage that refinement of the biocatalyst though enzyme engineering will reduce the amine loading for expedient CR-RA as well as expand the substrate scope. This reaction further expands the repertoire of IREDs and emphasises their importance in the synthesis of stereochemically defined chiral amines.

References

1. The new drugs of 2019. *C&EN Glob. Enterp.* **98**, 30–36 (2020).

2. Afanasyev, O. I., Kuchuk, E., Usanov, D. L. & Chusov, D. Reductive Amination in the Synthesis of Pharmaceuticals. *Chem. Rev.* **119**, 11857–11911 (2019).

3. Marshall, J. R. *et al.* Screening and characterization of a diverse panel of metagenomic imine reductases for biocatalytic reductive amination. *Nat. Chem.* **13**, 140–148 (2021).

4. Roughley, S. D. & Jordan, A. M. The medicinal chemist's toolbox: An analysis of reactions used in the pursuit of drug candidates. *J. Med. Chem.* **54**, 3451–3479 (2011).

5. Yasukawa, T., Masuda, R. & Kobayashi, S. Development of heterogeneous catalyst systems for the continuous synthesis of chiral amines via asymmetric hydrogenation. *Nat. Catal.* **2**, 1088–1092 (2019).

6. Wu, Z. *et al.* Secondary amines as coupling partners in direct catalytic asymmetric reductive amination. *Chem. Sci.* **10**, 4509–4514 (2019).

7. Skrypai, V., Varjosaari, S. E., Azam, F., Gilbert, T. M. & Adler, M. J. Chiral Brønsted Acid-Catalyzed Metal-Free Asymmetric Direct Reductive Amination Using 1-Hydrosilatrane. *J. Org. Chem.* **84**, 5021–5026 (2019).

8. Aleku, G. A. *et al.* A reductive aminase from Aspergillus oryzae. *Nat. Chem.* **9**, 961–969 (2017).

9. Mayol, O. *et al.* A family of native amine dehydrogenases for the asymmetric reductive amination of ketones. *Nat. Catal.* **2**, 324–333 (2019).

10. Yang, Y., Cho, I., Qi, X., Liu, P. & Arnold, F. H. An enzymatic platform for the asymmetric amination of primary, secondary and tertiary C(sp 3)–H bonds. *Nat. Chem.* **11**, 987–993 (2019).

11. Li, T. *et al.* Efficient, Chemoenzymatic Process for Manufacture of the Boceprevir Bicyclic [3.1.0]Proline Intermediate Based on Amine Oxidase-Catalyzed Desymmetrization. *J. Am. Chem. Soc.* **134**, 6467–6472 (2012).

12. Zhou, J. & List, B. Organocatalytic Asymmetric Reaction Cascade to Substituted Cyclohexylamines. *J. Am. Chem. Soc.* **129**, 7498–7499 (2007).

13. Monti, D. *et al.* Cascade Coupling of Ene-Reductases and ω-Transaminases for the Stereoselective Synthesis of Diastereomerically Enriched Amines. *ChemCatChem* **7**, 3106–3109 (2015).

14. France, S. P., Hepworth, L. J., Turner, N. J. & Flitsch, S. L. Constructing Biocatalytic Cascades: In Vitro and in Vivo Approaches to de Novo Multi-Enzyme Pathways. *ACS Catal.* **7**, 710–724 (2017).

15. Huffman, M. A. *et al.* Design of an in vitro biocatalytic cascade for the manufacture of islatravir. *Science.* **366**, 1255–1259 (2019).

16. Toogood, H. S. & Scrutton, N. S. Discovery, Characterization, Engineering, and Applications of Ene-Reductases for Industrial Biocatalysis. *ACS Catal.* **8**, 3532–3549 (2018).

17. Roth, S., Kilgore, M. B., Kutchan, T. M. & Müller, M. Exploiting the Catalytic Diversity of Short-Chain Dehydrogenases/Reductases: Versatile Enzymes from Plants with Extended Imine Substrate Scope. *ChemBioChem* **19**, 1849–1852 (2018).

18. Hyslop, J. F. *et al.* Biocatalytic Synthesis of Chiral *N*-Functionalized Amino Acids. *Angew. Chemie. Int. Ed.*

57, 13821–13824 (2018)

19. Kato, Y., Yamada, H. & Asano, Y. Stereoselective synthesis of opine-type secondary amine carboxylic acids by a new enzyme opine dehydrogenase use of recombinant enzymes. *J. Mol. Catal. B Enzym.* **1**, 151–160 (1996).

20. Schober, M. *et al.* Chiral synthesis of LSD1 inhibitor GSK2879552 enabled by directed evolution of an imine reductase. *Nat. Catal.* **2**, 909–915 (2019).

21. Bornadel, A. *et al.* Technical Considerations for Scale-Up of Imine-Reductase-Catalyzed Reductive Amination: A Case Study. *Org. Process Res. Dev.* **23**, 1262–1268 (2019).

22. Hussain, S. *et al.* An (R)-Imine Reductase Biocatalyst for the Asymmetric Reduction of Cyclic Imines. *ChemCatChem* **7**, 579–583 (2015).

23. Yao, P., Xu, Z., Yu, S., Wu, Q. & Zhu, D. Imine Reductase-Catalyzed Enantioselective Reduction of Bulky *α*,*β*-Unsaturated Imines en Route to a Pharmaceutically Important Morphinan Skeleton. *Adv. Synth. Catal.* **361**, 556–561 (2019).

24. Mitsukura, K. *et al.* Purification and Characterization of a Novel (R)-Imine Reductase from Streptomyces sp. GF3587. *Biosci. Biotechnol. Biochem.* **75**, 1778–1782 (2011).

25. Lenz, M. *et al.* Asymmetric Ketone Reduction by Imine Reductases. *ChemBioChem* **18**, 253–256 (2017).

26. Thorpe, T. W. *et al.* One-Pot Biocatalytic Cascade Reduction of Cyclic Enimines for the Preparation of Diastereomerically Enriched N -Heterocycles. *J. Am. Chem. Soc.* **141**, 19208–19213 (2019).

27. Steiningerova, L. *et al.* Different Reaction Specificities of F420 H2-Dependent Reductases Facilitate Pyrrolobenzodiazepines and Lincomycin To Fit Their Biological Targets. *J. Am. Chem. Soc.* **142**, 3440–3448 (2020).

28. Trenti, F., Yamamoto K., Hong B., Paetz C., Nakamura Y., & O'Connor S. E. Early and Late Steps of Quinine Biosynthesis. *Org. Lett.* **23** 1793–1797 (2021).

29. Mitsukura, K., Suzuki, M., Tada, K., Yoshida, T. & Nagasawa, T. Asymmetric synthesis of chiral cyclic amine from cyclic imine by bacterial whole-cell catalyst of enantioselective imine reductase. *Org. Biomol. Chem.* **8**, 4533 (2010).

30. France, S. P. *et al.* Identification of Novel Bacterial Members of the Imine Reductase Enzyme Family that Perform Reductive Amination. *ChemCatChem* **10**, 510–514 (2018).

31. Mangas-Sanchez, J. *et al.* Asymmetric synthesis of primary amines catalyzed by thermotolerant fungal reductive aminases. *Chem. Sci.* **11**, 5052–5057 (2020).

32. Montgomery, S. L. *et al.* Characterization of imine reductases in reductive amination for the exploration of structure-activity relationships. *Sci. Adv.* **6**, 9320 (2020).

33. Ouellet, S. G., Walji, A. M. & Macmillan, D. W. C. Enantioselective Organocatalytic Transfer Hydrogenation Reactions using Hantzsch Esters. *Acc. Chem. Res.* **40**, 1327–1339 (2007).

34. Santi, N., Morrill, L. C., Świderek, K., Moliner, V. & Luk, L. Y. P. Transfer hydrogenations catalyzed by streptavidin-hosted secondary amine organocatalysts. *Chem. Commun.* **57**, 1919–1922 (2021).

35. Rodríguez-Mata, M. *et al.* Structure and Activity of NADPH-Dependent Reductase Q1EQE0 from Streptomyces kanamyceticus, which Catalyses the *R*-Selective Reduction of an Imine Substrate. *ChemBioChem* **14**, 1372–1379 (2013).

36. Holm, L. Benchmarking fold detection by DaliLite v.5. *Bioinformatics* **35**, 5326–5327 (2019).

37. Lenz, M. *et al.* New imine-reducing enzymes from *β*-hydroxyacid dehydrogenases by single amino acid substitutions. *Protein Eng. Des. Sel.* **31**, 109–120 (2018).

38. Huber, T. *et al.* Direct Reductive Amination of Ketones: Structure and Activity of *S*-Selective Imine Reductases from *Streptomyces*. *ChemCatChem* **6**, 2248–2252 (2014).

39. Man, H. *et al.* Structure, activity and stereoselectivity of NADPH-dependent oxidoreductases catalysing the S-selective reduction of the imine substrate 2-methylpyrroline. *ChemBioChem* **16**, 1052–1059 (2015).

40. Aleku, G. A. *et al.* Stereoselectivity and Structural Characterization of an Imine Reductase (IRED) from *Amycolatopsis orientalis*. *ACS Catal.* **6**, 3880–3889 (2016).

41. Trott, O. & Olson, A. J. AutoDock Vina: Improving the speed and accuracy of docking with a new scoring function, efficient optimization, and multithreading. *J. Comput. Chem.* **31**, 455–461 (2009).

Figure legends

Fig.1 | Enantioenriched amine diastereomers and enzymatic one-pot strategies for their synthesis. a: enantioenriched amine diastereomers are common in APIs, **b**: one-pot strategies for the enzymatic synthesis of stereoenriched amine diastereomers, **c**: our approach for developing a single enzyme-catalysed conjugate reduction-reductive amination (CR-RA) to prepare enantioenriched amine diastereomers, **d**: identification of C=C and C=N reducing EneIRED (pIR-120) by screening 389 putative IREDs, **e**: optimised reaction conditions for EneIRED-catalysed CR-RA, see Extended Data Fig. ED1 and ED2 and Supplementary Information for further details.

Fig. 2 | Substrate scope of EneIRED-catalysed CR-RA. Major RA product is drawn, product distribution is illustrated by the donut chart, % conversion = ∑(area% of CR and RA products). [a]non-enzymatic aza-conjugate addition product observed, [b]certain components determined by analogy based on the GC-MS spectrum, see Supplementary Table S2 for further details.

Fig. 3 | Mechanistic and structural studies. a: deuterium labelling experiment, **b**: amine donor control experiments, **c**: structure of EneIRED dimer in ribbon format with monomers A and B respectively in green and blue, **d**: Active site of EneIRED in complex with $NADP^+$ with side chains of monomers A and B are shown in cylinder format with carbon atoms respectively in green and blue. The structure has been used to model the ene-imine ligand (the condensation product of **15** and **b**), shown with carbon atoms in yellow. The distance between these atoms is given in Ångstroms, **e**: Reactions of EneIRED point variants in reaction with **15** and **b** under standard conditions.

Fig. 4 | Proposed catalytic cycle of productive EneIRED conjugate reduction-reductive amination (CR-RA) and extension to 6-electron CR-RA. a: schematic of the proposed catalytic cycles for EneIRED-catalysed CR and RA demonstrating the productive CR-RA reaction of α,β-unsaturated carbonyls with amines, **b**: example of 6-electron enzymatic CR-RA catalysed by EneIRED only, by-product formation observed, see Supplementary Information for further details.

Methods

Cloning, expression and protein purification

The codon-optimised EneIRED gene sequence (TWIST Biosciences, US, GenBank accession number MW854365) was cloned into pET-28a-(+) (Supplementary Fig. SF1) and used to transform chemically competent *E. coli* BL21 (DE3). Point variants of EneIRED were created by site-directed mutagenesis using appropriate primers, see Supplementary Information (1.5 and 2.2). Cultivation was performed in 400 mL Terrific Broth (TB) media (Formedium, Hunstanton, Norfolk, UK) supplemented with 35 $\mu g \cdot mL^{-1}$ kanamycin in 2 L Erlenmeyer baffled flasks. Cultures were incubated at 37 °C and shaken at 200 rpm until an optical density (OD_{600nm}) of 0.6-0.8, before gene

expression was induced with isopropyl *β*-*D*-1-thiogalactopyranoside (IPTG) at a final concentration of 100 μM. Incubation was continued at 23 °C and 200 rpm for 25 h before harvesting the biomass using centrifugation. Disruption of the cells using sonication in an ice bath, then clarification by centrifugation and lyophilisation afforded powdered EneIRED cell-free extract (CFE). To obtain purified enzyme, EneIRED CFE was resuspended, clarified by centrifugation and immobilised metal affinity chromatography (IMAC) was performed. Further purification of the protein for crystallography and control and mechanistic experiments was realised using gel filtration (GF) chromatography. For further details see Supplementary Information.

Biotransformations

Typical procedure for EneIRED-catalysed CR-RA: A 200 μL reaction mixture consisting of 10 mM *α*,*β*-unsaturated carbonyl, 200 mM amine, 0.2 mol% EneIRED, 0.1 mg·mL^{-1} GDH, 5.0 mol% NADP$^+$, 30 mM glucose, 15% v/v DMSO, 100 mM glycine-NaOH buffer pH 9.0 were shaken at 900 rpm in 96-well microtiter plate at 30 °C for 18 h before being quenched with 5.0 M NaOH (aq., 20 μL) and extracted into heptane, dichloromethane or $CDCl_3$ (2 × 200 μL). The organic fractions were combined and analysed by GC-MS before being derivatised and analysed by GC-FID over a chiral stationary phase or ^{1}H NMR. CR-RA reactions were undertaken in 2–5 replicates and could also be performed using EneIRED CFE (4 mg·mL^{-1}) affording comparable results.

Screening the panel of IREDs was undertaken at 100 μL total reaction volume consisting of 5 mM of ene-imine **I**, 12.5 mg·mL^{-1} IRED, 0.1 mg·mL^{-1} GDH, 1.0 mol% NADP$^+$, 50 mM glucose in 100 mM KPi buffer pH 7.0 were shaken at 900 rpm in 384-well microtiter plate at 30 °C for 24h before being quenched with 5.0 M NaOH (aq., 10 μL), extracted into heptane (2 × 100 μL) and analysed by GC-MS. The product distributions were mapped to the phylogenetic IRED tree (Extended Data Fig. ED1) created using the Interactive Tree of Life (iTOL).[42]

Time course reactions were undertaken at 5 mM *α*,*β*-unsaturated carbonyl, 200 mM amine, 0.4 mol% EneIRED or EneIRED point variants, 0.1 mg·mL^{-1} GDH, 10 mol% NADP$^+$, 30 mM glucose, 15% v/v DMSO, 100 mM glycine-NaOH buffer pH 9.0 and were shaken at 250 rpm in a 2 mL Eppendorf at 30 °C. At each time point 100 μL of the reaction was removed and basified with 5.0 M NaOH (aq., 10 μL) before extraction into heptane (2 × 200 μL) and analysis by GC-MS.

Preparative scale reactions were undertaken at 10 or 50 mM *α*,*β*-unsaturated carbonyl with 200-250 mM amine, 0.2 or 0.1 mol% EneIRED, 0.1 mg·mL^{-1} GDH, 1.0 mol% NADP$^+$, 30 or 150 mM glucose, 15% v/v DMSO, 100 mM glycine-NaOH buffer pH 9.0 at a volume of 30 mL or 50 mL and were shaken at 200 rpm in falcon tubes at 25 °C for 24 h before being quenched with 5.0 M NaOH (aq., 0.1 × reaction volume), clarified by centrifugation and extracted

into MTBE (3 × reaction volume). The organic fractions were combined, dried with $MgSO_4$ and concentrated under reduced pressure to remove excess amine substrate before acidification with 2.0 M HCl (dioxane, 2 eq.) and concentration *in vacuo* to yield the amine-HCl salt which was analysed by NMR and GC-FID over a chiral stationary phase. For further details see Supplementary Information.

Protein crystallography data collection, structure solution and refinement

Initial screening of crystallization conditions was performed using commercially available INDEX (Hampton Research), PACT premier and CSSI/II (Molecular Dimensions) screens in 96-well sitting drop trays. Optimization was carried out in a 24-well hanging-drop format to obtain crystals for X-ray diffraction studies. For co-crystallization experiments, a 200 mM stock solution of cosubstrate $NADP^+$ in water was prepared.

Crystals of the wt-EneIRED-$NADP^+$ complex were grown using wt-EneIRED concentrated to 35 $mg \cdot mL^{-1}$ in 50 mM Tris buffer pH 7.5 containing 300 mM NaCl. The crystallisation drop contained 0.15 µL protein: 0.15 µL mother liquor, comprising 100 mM Tris buffer pH 6.5, 25% (w/v) PEG (polyethylene glycol) 3350, and 5.0 mM $NADP^+$. Crystals were harvested directly into liquid nitrogen with nylon CryoLoops™ (Hampton Research), using the mother liquor containing 10% (v/v) ethylene glycol as cryoprotectant.

The dataset described in this report was collected at the Diamond Light Source, Didcot, Oxfordshire, U.K. on beamline I03, at a temperature of 120 K and a wavelength of 0.97625 Angstroms. Data were processed and integrated using XDS S7 and scaled using SCALA S8 included in the Xia2 processing system.S9 Data collection statistics are provided in (Extended Data Table 1). The crystal of EneIRED-$NADP^+$ was obtained in space group P21, with two molecules in the asymmetric unit; the solvent content in the crystals was 42%. The structure of the EneIRED-$NADP^+$ was solved by molecular replacement using MOLREPS10 with the monomer of *At*RedAm (PDB code 6EOD)[43] as the model. The structure was built and refined using iterative cycles in Coot[44] and REFMAC,[45] employing local NCS restraints in the refinement cycles. Following building and refinement of the protein and water molecules in this complex, residual density was observed in the omit maps at the dimer interfaces, which could be clearly modelled as $NADP^+$. The final structures exhibited % Rcryst /Rfree values of 19.0/23.0. Refinement statistics for the structures are presented in (Extended Data Table 1). The Ramachandran plot for EneIRED-$NADP^+$ showed 96.5% of residues to be situated in the most favoured regions, 3.0% in additional allowed and 0.5% residues in outlier regions. The structure has been deposited in the Protein Databank (PDB) with accession code 7A3W

Methods References

42. Ivica Letunic & Peer Bork, Interactive Tree Of Life (iTOL) v5: an online tool for phylogenetic tree display and annotation, *Nucleic Acids Res.* **49**, W293–W296, (2021).

43. Sharma, M. *et al.* A Mechanism for Reductive Amination Catalyzed by Fungal Reductive Aminases. *ACS Catal.* **8**, 11534–11541 (2018).

44. Emsley, P. & Cowtan, K. Coot : model-building tools for molecular graphics. *Acta Crystallogr. Sect. D Biol. Crystallogr.* **60**, 2126–2132 (2004).

45. Murshudov, G. N., Vagin, A. A. & Dodson, E. J. Refinement of Macromolecular Structures by the Maximum-Likelihood Method. *Acta Crystallogr. Sect. D Biol. Crystallogr.* **53**, 240–255 (1997).

Extended Data Figure Legends

Extended Data Fig. ED1 |

Title: Phylogenetic IRED tree mapped against the reaction profiles of IRED-catalysed reduction of ene-imine **I**.

Legend: Whilst the majority of the IREDs catalysed conventional imine reduction only, a small number were able to reduce both C=C and C=N bonds. Of these, EneIRED (pIR-120) possessed the highest propensity at forming the desired amine **II**.

Extended Data Fig. ED2 |

Title: Optimisation of EneIRED-catalysed CR-RA reaction conditions.

Legend: Conversion to the products of CR and CR-RA were elevated in glycine-OH pH 9.0, at moderate DMSO cosolvent concentration and at higher equivalents of amine donor. Formation of the direct RA product was not observed under any conditions.

Extended Data Fig. ED3 |

Title: Scaled-up examples of EneIRED-catalysed CR-RA.

Legend: Several secondary and tertiary amines could be prepared including an example at elevated enone concentration and lower amine equivalents.

Extended Data Fig. ED4 |

Title: Control reactions and isolated reactions of potential CR-RA pathway intermediates in EneIRED catalysed CR-RA.

Legend: **a**: EneIRED CR-RA of **15** and **b** with NADPH, **b**: no enzyme control reaction, **c**: no recycling system control reaction, **d**: reactions of potential CR-RA intermediate **15b** with $NADP^+$ or NADPH, **e**: Reaction of potential CR-RA intermediate **15'** with **b** using EneIRED, **f**: no amine control reactions with EneIRED point variants.

Extended Data Fig. ED5 |

Title: Time course studies of the CR-RA of **15** with **b** catalysed by wild-type EneIRED and point variants.

Legend: Both EneIRED-Y177A and EneIRED-Y181A exhibited a reduction in the rate of CR and CR-RA product formation compared to wild-type EneIRED, indicating that both residues are important for efficient catalysis. Notably, for EneIRED-Y177A the concentration of the ketone intermediate was comparatively low throughout the reaction, suggesting that Y177 is more important for CR than RA.

Extended Data Fig. ED6 |

Title: Active site of EneIRED highlighting electron density.

Legend: **A**: side chains, with density corresponding to the refined $2F_o$-F_c map (blue) at a level of 1σ; **B**: $NADP^+$, with density corresponding to the F_o-F_c difference map (green) at a level of 3σ obtained from refinement in the absence of the ligand, with refined atoms included for clarity.

Extended Data Table 1 |

Title: Data collection and refinement statistics (molecular replacement) for EneIRED in complex with $NADP^+$.

Legend: 1 crystal was used to obtain this dataset. *Values in parentheses are for highest-resolution shell.

Data Availability and Code Availability Statement

The data supporting the findings of this study are available within the paper and its Supplementary Information files and NMR traces are available from the Mendeley data repository (https://data.mendeley.com) at doi: 10.17632/fhc429t33c.1. Sequence data has been deposited in Genbank (accession numbers MW854365, MW925135-MW925140) and the coordinate files and structure factors have been deposited in the PDB with coordinate (accession number 7A3W).

Additional Information

Supplementary Information is available for this paper. Correspondence and requests for materials should be addressed to N.J.T. Reprints and permissions information is available at www.nature.com/reprints. The authors declare no competing interests.

Acknowledgements

T.W.T. is grateful for a CASE award from the UK Biotechnology and Biological Sciences Research Council (BBSRC) and Pfizer (BB/M011208/1). J.R.M. acknowledges a CASE award from the Industrial Biotechnology Innovation Centre (IBioIC), BBSRC, and Prozomix Ltd. A.C. was funded by grant BB/P005578/1 from the BBSRC. N.J.T. is grateful to the ERC for the award of an Advanced Grant (742987). We thank Dr Johan P. Turkenburg and Mr Sam Hart for assistance with X-ray data collection and the Diamond Light Source for access to beamline I03 under proposal number mx-9948.

Author Contributions

N.J.T., G.G., R.M.H., R.K., D.S.B.D. devised and supervised the project. F.P. and R.E.R. managed the project. T.W.T. and A.A performed mechanistic studies. T.W.T. and R.E.R carried out substrate scope reactions. T.W.T. and V.H. carried out preparative scale reactions. T.W.T., R.E.R and V.H. synthesised substrates and standards. A.C., T.W.T. and G.G. performed crystallographic and docking studies. T.W.T. and R.S.H undertook site-directed mutagenesis. J.R.M., S.J.C., J.D.F. performed genetic identification, cloning and bioinformatics. T.W.T. and J.R.M. produced and purified the biocatalyst, N.J.T, G.G., R.M.H., R.K, D.S.B.D., S. J. C., F.P. J.D.F., A.C, R.E.R., V.H., J.R.M. and T.W.T. wrote the manuscript and generated the figures.