CRISPR-Cas12a/Cpf1-assisted precise, efficient and multiplexed genome-editing in Yarrowia lipolytica

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Abstract

CRISPR-Cas9 has been widely adopted as the basic toolkit for precise genome-editing and engineering in various organisms. Alternative to Cas9, Cas12 or Cpf1 uses a simple crRNA as a guide and expands the protospacer adjacent motif (PAM) sequence to TTTN. This unique PAM sequence of Cpf1 may significantly increase the on-target editing efficiency due to lower chance of Cpf1 misreading the PAMs on a high GC genome. To demonstrate the utility of CRISPR-Cpf1, we have optimized the CRISPR-Cpf1 system and achieved high-editing efficiency for two counter-selectable markers in the industrially-relevant oleaginous yeast Yarrowia lipolytica: arginine permease (93% for CAN1) and orotidine 5’-phosphate decarboxylase (~96% for URA3). Both mutations were validated by indel mutation sequencing. For the first time, we further expanded this toolkit to edit three sulfur house-keeping genetic markers (40%-75% for MET2, MET6 and MET25), which confers yeast distinct colony color changes due to the formation of PbS (lead sulphide) precipitates. Different from Cas9, we demonstrated that the crRNA transcribed from a standard type II RNA promoter was sufficient to guide Cpf1 endonuclease activity. Furthermore, modification of the crRNA with 3’ polyUs facilitates the faster maturation and folding of crRNA and improve the genome editing efficiency. We also achieved multiplexed genome editing, and the editing efficiency reached 75%-83% for duplex genomic targets (CAN1-URA3 and CAN1-MET25) and 41.7% for triplex genomic targets (CAN1-URA3-MET25). Taken together, this work expands the genome-editing toolbox for oleaginous yeast species and may accelerate our ability to engineer oleaginous yeast for both biotechnological and biomedical applications.

1. Introduction

Y. lipolytica, as a promising oleaginous yeast cell factory, has been extensively engineered for the production of lipids (Qiao et al., 2017; Xu et al., 2017a,b), oleochemicals (Xu et al., 2016), drop-in transportation fuels (Xu et al., 2016) and commodity chemicals (Blazeck et al., 2015; Wang et al., 2019) recently. It is known as a ‘generally regarded as safe’ (GRAS) organism for the production of organic acids and polyunsaturated fatty acids (PUFAs) (Bailey et al., 2010; Sharpe et al., 2014) in the food and nutraceutical industry. Compared to S. cerevisiae, Y. lipolytica lacks Crabtree effects, without generation of ethanol under high glucose conditions. The low pH tolerance (Cui et al., 2017), strictly aerobic nature (Abghari and Chen, 2014; Ledesma-Amaro et al., 2016) and versatile substrate-degradation profile (Ledesma-Amaro et al., 2016; Li and Alper, 2016; Rodriguez et al., 2016) enable its robust growth from a wide range of renewable feedstocks, including pentose (Ledesma-Amaro et al., 2016; Li and Alper, 2016; Rodriguez et al., 2016), crude glycerol (Gao et al., 2016a,b; Dimitris et al., 2019), glacial acetic acids (Xu et al., 2017a,b; Liu et al., 2019a,b) and volatile fatty acids (VFA) (Spagnuolo et al., 2018) et al. Unlike bacteria, the spatially-organized subcellular compartment and hydrophobic lipid bodies in oleaginous yeast provide the ideal environment for the regioselectivity and stereoselectivity of many plant-specific P450 enzymes (Lv et al., 2019a,b). Due to the strong endogenous acetyl-CoA and malonyl-CoA flux, Y. lipolytica has been harnessed as an industrial workhorse for efficient synthesis of complex plant secondary metabolites including polyketides (Markham et al., 2018; Liu et al., 2019a,b), flavonoids (Lv et al., 2019a,b), carotenoids (Gao et al., 2017; Larroude et al., 2018) and terpenoids (Jin et al., 2019).

Phylogenetically distant from Baker’s yeast and S. Pombe, Y. lipolytica carries 6 chromosomes with 57%-59% GC content in the coding sequence and a total genome size of 20.5 Mb (Barth and Gaillardin, 2018).
et al., 2018), Piggybac transposon (Wagner et al., 2018), iterative gene
Wong et al., 2019), Golden-gate cloning (Celi
2017; Jang et al., 2018), YaliBrick-based cloning (Wong et al., 2017;
Blazeck et al., 2013; Liu et al., 2019a,b), gene deletions (Bredeweg et al.,
to
lipid oxidation and VFA detoxi
Due to its prominent industrial potential, a signi
cant amount has been focused to develop genetic toolbox in this yeast, ranging
from protein expression (Juretzek et al., 2001; Nicaud et al., 2002;
Bordes et al., 2007), promoter characterization (Blazeck et al., 2011;
Blazeck et al., 2013; Liu et al., 2019a,b), gene deletions (Bredeweg et al.,
Jang et al., 2018), YaliBrick-based cloning (Wong et al., 2017;
Wong et al., 2019), Golden-gate cloning (Celińska et al., 2017; Larroude
et al., 2018), Piggybac transposon (Wagner et al., 2018), iterative gene
integration (Gao et al., 2017; Lv et al., 2019a,b) to
CRISPR/Cas9-mediated genome-editing (Schwartz et al., 2017; Wong
et al., 2017; Holkenbrink et al., 2018; Morse et al., 2018) et al. This
generic toolbox affords us a collection of facile genetic tools for stream-
lined and accelerated pathway engineering in oleaginous yeast species.

Despite that the
Streptococcus pyogenes
(Sp) CRISPR-Cas9 system has been widely adapted for genome editing in multiple yeast species, including bakers’ yeast (DiCarlo et al., 2013; Jakociunas et al., 2015; Mans et al., 2015; Si et al., 2017), the pathogenic yeast
Candida albicans
(Vyas et al., 2015; Min et al., 2016; Ng and Dean, 2017; Shapiro et al.,
2018), the basidiomycetous yeast
Rodosporidium toruloides
(Jiao et al., 2019; Otoupal et al., 2019; Schultz et al., 2019), and oleaginous yeast
Y. lipolytica
(Schwartz et al., 2017; Wong et al., 2017; Holkenbrink et al.,
2018; Morse et al., 2018) et al. the adoption of the recently discovered
CRISPR-Cas12/cpf1 (Zetsche et al., 2015; Zetsche et al., 2017; Chen
et al., 2018) as genome-editing tools in oleaginous yeast has been
significantly lagging behind. The CRISPR-Cpf1 system is complementary
to Cas9 with several advantages. Cas9 predominantly recognizes purine
rich PAMs (NGG) and cleaves target DNA upstream of PAMs to generate
blunt-end DSBs (double strand breaks) (Cong et al., 2013). In contrast,
Cpf1 primarily recognizes T-rich PAMs (TTTN) and cuts DNA in a stagg-
ered pattern downstream of the targeted sequence to generate sticky
ends (Fig. 1), leaving behind 4–5 nt 5’-overhangs (Zetsche et al., 2015).
NHEJ (non-homologous end joining repair) usually destroys the PAM site
in Cas9 cutting due to its close proximity to the cleavage site, thus
preventing future edits and making it difficult for Cas9 re-targeting. Unlike
Cas9, Cpf1 cleaves the target DNA 18–23 nt downstream of the PAM.
During NHEJ repair with Cpf1 cutting, the PAM site will be retained and
Cpf1 may perform repeated editing (or second chance editing) for the
same genetic target. The repeated cutting of Cpf1 may enrich the cleav-
age events and improve its on-target editing efficiency. Efficient cutting
in Cas9 sgRNA also requires the proper folding of tracrRNA (trans-
activating CRISPR RNA) and crRNA. Unlike Cas9, Cpf1 only use a 20 nt
DR (directed repeat) sequence preceding the crRNA. Without the 80 nt
tracrRNA, this simple crRNA in Cpf1 allows us to deliver the guide RNA
much more efficiently than we can deliver the sgRNA in the Cas9 system.
The expanded PAM sequence space, stuttered cutting patterns and the
simplified crRNA structures make Cpf1 an attractive complementation to
enable broader and improved targeting opportunities for oleaginous
species.

In this work, we demonstrated that AsCpf1 could efficiently introduce
nucleotide substitutions, insertions and gene deletions with high effi-
ciency and accuracy in a multiplexed manner. Various promoters ranging
from type II promoter flanked with ribozymes, type II promoter without
ribozymes, type III hybrid SCR1·rRNA and the SrrNA pro-

2. Results and discussions

2.1. CRISPR-Cpf1 mediated in-del mutations of counter-selectable marker
CAN1

As a proof-of-concept to test the genome-editing efficiency of
the CRISPR-Cpf1 system in
Y. lipolytica,
we first targeted the CAN1 gene
(encoding arginine permease). Arginine permease (CAN1) is responsible
for the yeast to assimilate arginine from the media. Anti-metabolite, L-

Fig. 1. Crisp-cas12/cpf1 recognizes TTTN protospacer adjacent motif (PAM) and is guided by a simple crRNA without the need for tracrRNA (trans-activating
CRISPR RNA). Cpf1 introduces double strand break (DSB) in a staggered pattern and generate sticky ends. The DSB is primarily repaired by non-homologous end
joining (NHEJ) in
Y. lipolytica.
using this crRNA expression strategy (Fig. 2C), which achieved higher editing efficiency than that of using Cas9 with the same crRNA expression strategy in our previous work (Wong et al., 2017; Wong et al., 2019).

Genome editing of CAN1 gene has been reported in other studies. Bao et al. described the editing of CAN1 ranging from 14.71% using a 100 bp donor DNA to 100% when prolonged incubation in liquid media was performed in S. cerevisiae (Bao et al., 2014). Similarly, in-del mutation of CAN1 in Y. lipolytica was only found to be 7–10% in the CRISPR-Cas9 system (Wong et al., 2017; Wong et al., 2019), when the sgRNA was flanked with 5’ HHR and 3’ HDV from the strong TEF/intron promoter. In a recent study, targeting efficiency of CAN1 by Cas9 achieved 60% using a T7 promoter in Y. lipolytica (Morse et al., 2018). Compared with extant strategies, the CRISPR-AsgF1 system demonstrated superior editing efficiency to introduce in-del mutations in Y. lipolytica, and prolonged incubation was not necessary. Potentially, this CRISPR-AsgF1 system could be implemented in a relatively shorter timescale with high editing efficiency.

2.2. Optimizing crRNA expression to improve CRISPR-Cpf1 targeting efficiency

CRISPR RNA (crRNA) belongs to non-coding RNA and transcription of crRNA was found to be critical for CRISPR genome editing. A modified type II promoter such as the TEF promoter or a type III promoter such as the hybrid SNR52 promoter or the U6 promoter, is generally used to drive the expression of sgRNA or crRNA. We demonstrated that the type II promoter (TEF-intron with ribozymes) could achieve relatively high genome-editing efficiency (Fig. 2). To provide the optimal crRNA transcript, we constructed three additional crRNA constructs for CAN1 targeting (Fig. 2A): (I) TEF-intron promoter without 5’ HHR or 3’ HDV ribozymes; (II) the hybrid promoter SCR1-rRNA-Gly (Schwartz et al., 2016) and (III) the 5s rRNA promoter (Schultz et al., 2019). Interestingly, the crRNA expressed by TEF-intron promoter without ribozymes reached 93.3% ± 11.5% (10/10, 10/10, 8/10) editing efficiency (Fig. 2C). This indicated that Cpf1 alone is sufficient to process crRNA and generate mature crRNA for Cpf1 targeting, which is consistent with recent findings that Cpf1 was able to process pre-crRNA arrays to form mature crRNA.

Fig. 2. Crispr-cas12/cpf1-mediated genome-editing of dominant marker arginine permease encoded by CAN1. (A) Four genetic configurations of crRNA promoter were tested to drive the expression of crRNA-CAN1. (B) Type II RNA promoter (TEF) were flanked with upstream hammer head ribozyme and downstream HDV ribozyme to drive the expression of crRNA-CAN1. Ribozyme self-cleavage site has been marked with a scissor. (C) On-target genome-editing efficiency for CAN1 with four crRNA promoter configurations. N = 3, the reported data represents mean ± sd. (D) Sanger DNA sequencing to validate the on-target insertion or deletion (indels) mutations for CAN1 loci.
The mis-targeting on the endogenous URA3 remnants, we CAN1 using the native promoter from (Zheng et al., 2018). To expand this work, we also tested the feasibility of with a well-de URA3 gene (the endogenous RNA processing mechanism across different microbial hosts. only reaches 10%–20% (Fig. 2C), indicating that type III RNA polymerase supports the expression and processing of functional crRNAs. In a recent study, the short and abundant 5s ribosomal RNA (rRNA) was employed to drive the expression of sgRNA in Aspergillus niger with high genome-editing efficiency (Zheng et al., 2018). To expand this work, we also tested the feasibility of using the native promoter from Y. lipolytica, 5s rRNA, to express the crRNA of CAN1. The editing efficiency of CAN1 under the 5s rRNA promoter only reaches 10%–20% (Fig. 2C), indicating the complex non-coding RNA processing mechanism across different microbial hosts.

In summary, the type II TEF-intron promoter (without ribozymes) and the hybrid SCR1-rRNA™ promoter were identified as the most efficient promoters to drive the expression of crRNA in this CRISPR-Cpf1 system, leading to consistently high in-del editing of CAN1 up to 80%–90%. This efficiency represents a significantly improved gene-editing compared to previously reported CRISPR-Cas9 systems in oleaginous yeast species (Gao et al., 2016a,b; Wong et al., 2017; Wong et al., 2019).

2.3. CRISPR-Cpf1 mediated in-del mutations of counter-selectable marker URA3

We further tested another counter-selectable genetic marker to validate the functionality of CRISPR-Cpf1 in Y. lipolytica. The URA3 gene (encoding orotidine 5'-phosphate decarboxylase) is a commonly-used yeast genetic marker. URA3 mutants will require the supplementation of uracil, but develop resistance to the toxic 5'-fluoroorotic acid (5'-FOA). Since our host strain Y. lipolytica po1f carries a non-functional allele of URA3 gene (the endogenous URA3 was partially disrupted). To minimize the mis-targeting on the endogenous URA3 remnants, we first modified the po1f strain by replacing the ALK7 (encoding alkane oxidase) gene with a well-defined URA3 gene (Supplementary Fig. 1). This strain was subsequently used as the host for genome editing of URA3. Two types of crRNAs, URA3A and URA3B, targeting either the sense or the anti-sense strand, respectively, were designed and expressed using the TEF-intron promoter with ribozymes (Fig. 3A). 5'-FOA resistant colonies were harvested and used as template to amplify the edited URA3 gene. After sequencing of these PCR fragments, we identified in-del mutations at both the sense strand and nonsense strand (Fig. 3B and C). The hybrid SCR1-rRNA™ promoter led to about 100% disruption of URA3 using crRNA-URA3A. Similar editing efficiency was achieved with the TEF-intron promoter with ribozymes (Fig. 3A). These results reinforce that both polymerase II and III promoters can be used to drive the expression of crRNA in CRISPR-Cpf1 system, albeit editing efficiency may vary depending on the specific genetic targets (For instance, the CAN1 marker in previous section).

For screening and identifying the mutant colonies, we found that outgrowth is critical to enrich the genome-editing events. When transformation mixture was directly plated on CSM-Leu plate supplemented with 50 mg/L uracil and 1 mg/mL 5'-FOA, the CFU (colony forming unit) was drastically reduced. Less than ten colonies were obtained on the plate, possibly due to the high selection pressure of 5'-FOA and the slow cleavage activity of Cpf1: majority of cells were killed by 5'-FOA before they could be edited by Cpf1. It has been recently discovered that the addition of poly-thymidine to the 3'-end of crRNA could improve the AsCpf1 genome editing efficiency (Xie et al., 2015; Nowak et al., 2016, Bin Moon et al., 2018). We thus modified the crRNA by adding eight thymidine (T8), which will form a poly-U overhang following the 3'-end of the crRNA. CFUs were markedly improved by 10-fold over the original crRNA-URA3A after 2 days of outgrowth in CSM-Leu liquid media. URA3 editing efficiency reached 96% (10/10, 10/10, 9/10), indicating that the U-rich strategy could enhance the CRISPR-Cpf1 genome editing efficiency in Y. lipolytica (Fig. 3A), possibility due to the fast maturation of the crRNA in the presence of polyU. This is not surprising, as the formation of the Cpf1-crRNA-DNA nucleoprotein complex has been recently proposed as the major rate-limiting step for Cpf1 genome-editing (Strokendel et al., 2018). Either targeting to the sense strand (Fig. 3B) or the non-sense strand (Fig. 3C), we detected in-del mutations downstream of the TTTGs PAMs. Notably, control experiment was performed by directly plating the transformation mixture onto CSM-Leu plate without outgrowth. We observed that only 5%–7.5% disruption efficiency was achieved (Fig. 3A) for the control experiment. Outgrowth has been a commonly-used strategy to improve the CRISPR-Cas9 targeting efficiency of genes including TRPI (Gao et al., 2016a,b) and PEX10 (Schwartz et al., 2016) in Y. lipolytica. The URA3 mutants obtained after outgrowth showed different in-del mutations, which indicates that the improved efficiency was not due to enrichment of edited mutants. These results highlighted the critical role of outgrowth to enrich genome editing events for dominant and counter-selectable genetic markers, and the polyU-rich strategy could accelerate the maturation of functional crRNAs.
2.4. CRISPR-Cpf1 mediated in-del mutation of non-dominant markers

The methionine pathway starts with a number of sulfur housekeeping genes that sequentially reduce sulfate (SO$_4^{2-}$) to sulffite (SO$_3^{2-}$) and sulfide (S$^2-$) (Fig. 4A). Disruption of MET25 has been linked to the accumulation of sulfide (S$^2-$) intracellularly in both S. cerevisiae (Cost and Boeke, 1996) and C. albicans (Viaene et al., 2000). The yeast colony will form distinct black precipitate (lead sulffite PbS) if colorless and soluble lead (lead nitrate or lead acetate) salt was supplied to the media. This submersive marker has been used as a basic genetic tool to understand sulfur metabolism and methionine biosynthesis in various hosts.

The genome editing of CAN1 and URA3 was achieved by using counter-selectable marker with selection pressure (i.e. canavanine for CAN1 and 5'-FOA for URA3, respectively). To test the editing efficiency of CRISPR-Cpf1 without selection pressure, three submersive markers: MET25 (encoding homocysteine synthase), MET6 (encoding homocysteine methyltransferase) involved in methionine metabolism (Thomas and Surdin-Kerjan 1997) were targeted. After transforming Y. lipolytica po1g with the plasmid pYLXP–AsCpf1-crRNA-MET25, we observed that inactivation of MET25 indeed led the formation of black or brown colonies (Fig. 4B) in Y. lipolytica. Genome editing efficiency of 65% (13/20) was achieved after 7 days of incubation (Fig. 4B). It was also found that the black mutant cells were scattered around the white colonies (Fig. 4C), indicating the genome-editing events are not ubiquitous, and screening is essential to identify the genome-edited cells. To demonstrate the distinct phenotype, a Taichi or Ying-Yang bio-art has been created with the MET25 genome-edited cells and the wild type cells (Fig. 4D).

To test if the disruption of MET2 and MET6 could also lead to the black colony, three MET6 crRNA targets (crRNA-MET6A, crRNA-MET6B and crRNA-MET6A-U8) and two MET2 crRNA targets (crRNA-MET2A and crRNA-MET2B) were also designed and assembled into pYLXP–AsCpf1 plasmid. The precipitation of lead sulfide (PbS) and the formation of black colony were found for all these genetic targets, with varying efficiency. For practical applications, several guides should be designed and tested to achieve optimal gene disruption.

2.5. Multiplexed genome-editing with CRISPR-Cpf1

Compared to conventional chromosomal engineering method, including homology-based chromosomal integration (gene knock-in) or inactivation (gene knock-out or deletion), CRISPR provides us the opportunity to precisely edit multiple genomic targets, without the need of iterative marker recycling or curation. This multiplexed genome-editing is commonly achieved by placing an array of crRNAs or sgRNAs (Zhang et al., 2019). To test whether the CRISPR-Cpf1 system could achieve multiplexed genome editing in Y. lipolytica, we first investigated the simultaneous disruption of two genes. The crRNA expression cassettes of CAN1 and MET25 were assembled with the vector containing AsCpf1 (Fig. 5A and Supplementary Fig. S3). The double mutants were screened based on canavanine resistance and the formation of black colony. It was found that the efficiency of double mutant of CAN1 and MET25 reached 83.3% ± 5.7% (Fig. 5B). Similarly, the screening of double mutants of CAN1 and URA3 was performed based on canavanine resistance and 5'-FOA resistance. The double editing efficiency of CAN1 and URA3 was...
found to be 75% ± 5% (Fig. 5B). It should be noted that the URA3 genome-editing is enriched with cell outgrowth in uracil-rich media before the cells were screened against 5'-FOA or canavanine resistance.

We next sought to disrupt three genes with the crRNA targets for URA3, MET25 and CAN1. After cell outgrowth in uracil-rich media, the genome-edited cells were screened based on 5'-FOA or canavanine resistance (Supplementary Fig. 5A). We observed that the triplex editing efficiency reached 41.7% ± 7.6% (Fig. 5B). Despite that this editing efficiency is not high compared to multiplexed genome-editing in S. cerevisiae (Zhang et al., 2019), this efficiency (45%) would guarantee two positive triple mutants out of five colonies, which is sufficient for us to perform genome-editing and strain engineering in this yeast. Nevertheless, further optimization of the crRNA transcripts will be necessary for us to improve the multiplexed genome-editing efficiency.

3. Conclusions

In this work, we have tested an alternative genome-editing toolkit, CRISPR-Cas12/Cpf1, to perform genome-editing in Y. lipolytica. As a complementary toolbox to CRISPR-Cas9, we have achieved precise, efficient and multiplexed genome-editing with improved cleavage efficiency. The distinct PAM (TTTN) could expand gene-editing at AT-rich regions on genome. In addition, the simplification of black colony and canavanine resistance (Supplementary Table S1) made Rapid Screening of genome-edited mutants for CAN1, URA3 and MET25/

4. Methods and materials

4.1. Strains and growth conditions

E. coli NEB5α was routinely cultivated in Luria-Bertani (LB) broth and used for all cloning work. Y. lipolytica Po1f and Po1g were used as hosts for genome-editing. YPD medium consisting of 10 g/L yeast extract, 20 g/L peptone and 20 g/L Dextrose or complete synthetic media (CSM) lacking proper amino acid were used for yeast cultivation. For the selection of CAN1 mutants, 50 mg/L L-canavanine was supplemented in CSM-Ag plates. For the counter-selection of URA3 mutants, 50 mg/L uracil and 1 mg/mL 5'-fluoroorotic acid (5'-FOA) was added to CSM-Leu agar plates. MLA plates consisting of 3 g/L peptone, 5 g/L yeast extract, 0.2 g/L ammonium sulfate, 40 g/L glucose, 1 g/L lead nitrate and 20 g/L agar were used for visual selection of MET25, MET2 and MET6 mutants.

4.2. Plasmid construction

All primers (Supplementary Table S1) were listed in the use work were ordered from Integrated DNA Technologies (USA). All plasmids used in this study were listed in Supplementary Table S2. AsCpf1 was PCR amplified using pY010 as template and AsCpf1_F/AsCpf1_R as primers. The PCR product was designed to retain the nuclear localization signal (NLS) but the 3HA tag was removed. This PCR product was clean with Zymoclean kits and Gibson assembled into the SnaB1 and KpnI digested pYLPX2, to yield plasmid pYLPX-AsCpf1. To construct the crRNA for CAN1 targeting, AvrII-Fwd and Can1-crRR were used to PCR amplify the fragment crRNA-Can1up. SalI_Rvs and Can1-crRF were used to amplify the fragment crRNA-Can1dn. After PCR clean-up, crRNA-Can1up and crRNA-Can1dn were assembled with vector backbone pYLPX digested with AvrII and SalI using Gibson assembly to yield pYLPX-AscRNA-Can1. Other crRNA plasmids were constructed in a similar manner. All plasmids assembled by Gibson assembly were verified by Sanger sequencing (Genewiz, USA). To obtain all-in-one plasmid for genome editing, the crRNA constructs were digested with AvrII and Sall. The smallest fragment was gel-recovered and ligated with the NehI and Sall digested pYLPX-AsCpf1. All sub-cloned plasmids were verified by double digestion to match the pattern of the software (Benchling) predicted digestion pattern. All strains and plasmids constructed in this work is listed in Supplementary Table S2.

4.3. Screening of genome-edited mutants for CAN1, URA3 and MET25/ MET2/MET6

Colonies of Y. lipolytica Po1g transformed with pYLPX-AsCpf1-AscRNA-Can1 were picked up using sterile pipette tips and spotted on CSM-Ag plates supplemented with 50 mg/L L-canavanine. Colonies of Y. lipolytica Po1fΔALK7:URA3 transformed with pYLPX-AsCpf1-AscRNA-URA3A or pYLPX-AsCpf1-AscRNA-URA3B were spotted on CSM-Leu plates with 50 mg/L uracil and 1 mg/mL 5'-FOA. Colonies of Y. lipolytica Po1g transformed with pYLPX-AsCpf1-AscRNA-Met25 were spotted on MLA plates. For CAN1 or URA3 editing, incubation of 2–3 days allowed the formation of colonies on CSM-Ag plates. For MET25 targeting, longer incubation up to 5–6 days were required to form black colonies. All genome-editing experiments were performed in triplicates. Mean and standard deviations were reported in this work.

4.4. Screening for multiplexed genome editing

The crRNA expression cassette of MET25 and URA3A was subcloned into pYLPX-AsCpf1-AscRNA-CAN1 to result in pYLPX-AsCpf1-AscRNA-CAN1-MET25 and pYLPX-AsCpf1-AscRNA-CAN1-URA3A, respectively. The plasmids were transformed into Y. lipolytica po1g and po1fΔALK7:URA3, respectively. For the selection of can1 and met25 double mutants, yeast colonies were first spotted on CSM-Arg agar plates supplemented with L-canavanine. Positive colonies were replicated on MLA plates.

The screening of double mutants of CAN1 and URA3 was performed by growing the yeast transformation mixture in liquid CSM-Leu media supplemented with 50 mg/L uracil. After 4 days of outgrowth, cell culture was plated on CSM-Leu agar plate supplemented with 50 mg/L uracil and 1 mg/mL 5'-FOA. Positive colonies were spotted on CSM-Arg agar plate with L-canavanine.

Disruption of three genes was then investigated by subcloning of the crRNA-URA3A-U8 expression cassette into pYLPX-AsCpf1-AscRNA- CAN1-MET25 to yield pYLPX-AsCpf1-AscRNA-CAN1-MET25-UA3A-U8. This construct was transformed into strain po1fΔALK7:URA3. Transformation mixture was cultured in liquid CSM-Leu media supplemented with 50 mg/L uracil for 4 days. Cell culture was then plated on CSM-Leu agar plate with 50 mg/L uracil and 1 mg/mL 5'-FOA. After 2 days of incubation, 5'-FOA resistant colonies were screened on CSM-Arg + L-canavanine agar plate. The canavanine-resistant colonies were
subsequently streaked on MLA plates to identify MET25 mutations. All genome-editing experiments were performed in triplicates. Mean and standard deviations were reported in this work.

4.5. Y. lipolytica transformation and colony-PCR

Yeast transformation was performed using the lithium acetate method as previously described (Gaillardin et al., 1985). Transformation mixture was diluted and plated on proper agar plates and incubated for 2–3 days until colonies appeared. Yeast colonies were picked up and boiled in 10 μL 0.02 M sodium hydroxide for 10 min at 95 °C. Primers and Q5 PCR mix (New England Biolabs, USA) were added to perform colony PCR. PCR products were Sanger sequenced to identify in-del mutations.

Author contributions

PX conceived and supervised the work. ZLY and HE performed the studies. PX and ZLY wrote the manuscript with editing from HE.

Declaration of competing interest

A provisional patent has been filed based on the results of this study.

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Appendix A. Supplementary data

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References

Abghari, A., Chen, S., 2014. Yarrowia lipolytica as an oleaginous cell factory platform for the production of fatty acid-based biofuel and bioproducts. Front. Energy Res. 2.
Bayer, T.S., Smolke, C.D., 2005. Programmable ligand-controlled riboregulators of eukaryotic gene expression. Nat. Biotechnol. 23 (3), 337–343.
Bin Moon, S., Lee, J.M., Kang, J.G., Lee, N.E., Ha, D.I., Kim, D.Y., Kim, S.H., Yoo, K., Barth, G., Gaillardin, C., 1997. Physiology and genetics of the dimorphic fungus Yarrowia lipolytica. FEMS Microbiol. Rev. 19.
Bayer, T.S., Smolke, C.D., 2005. Programmable ligand-controlled riboregulators of eukaryotic gene expression. Nat. Biotechnol. 23 (3), 337–343.
Bredeweg, E.L., Pomraning, K.R., Dai, Z., Nielsen, J., Kerkhoven, E.J., Baker, S.E., 2017. Blazeck, J., Reed, B., Garg, R., Gerstner, R., Pan, A., Agarwala, V., Alper, H.S., 2013. Blazeck, J., Hill, A., Jamoussi, M., Pan, A., Miller, J., Alper, H.S., 2015. Metabolic engineering of Yarrowia lipolytica by a hybrid promoter approach. Proc. Natl. Acad. Sci. 112 (2), 450–455.
Chen, J.S., Ma, E., Harrington, L.B., Da Costa, M., Tian, X., Palefsky, J.M., Doudna, J.A., 2018. CRISPR-Cas12a target binding unleashes indistinguishable single-stranded DNA activity. Science 360 (6397), 436.
Morse, N.J., Wagner, J.M., Reed, K.B., Gopal, M.R., Lauffer, L.H., Alper, H.S., 2018. T7 polymerase expression of guide RNAs in vivo allows exportable CRISPR-cas9 editing in multiple yeast hosts. ACS Synth. Biol. 7 (4), 1075–1084.

Ng, H., Dean, N. 2018. Dramatic improvement of CRISPR/Cas9 editing in Candida albicans by increased single guide RNA expression. mSphere 2 (2).

Nicuad, J.M., Madzak, C., Broek, P., Gysler, C., Duboc, P., Niederberger, P., Gaillardin, C., 2002. Protein expression and secretion in the yeast Yarrowia lipolytica. FEMS Yeast Res. 2.

Nowak, C.M., Lawson, S., Zerez, M., Bleris, L., 2016. Guide RNA engineering for versatile Cas9 functionality. Nucleic Acids Res. 44 (20), 9555–9564.

Otoupal, P.B., Ito, M., Arkin, A.P., Magnuson, J.K., Gladden, J.M., Skerker, J.M., 2019. Multiplexed CRISPR-cas9-based genome editing of rhodospirillum toruloides. mSphere 4 (2) e00991-00019.

Qiao, K., Wasylenko, T.M., Zhou, K., Xu, P., Stephanopoulos, G., 2017. Lipid production in Yarrowia lipolytica is maximized by engineering cytosolic redox metabolism. Nat. Biotechnol. 35 (2), 173–177.

Rodriguez, G.M., Hussain, M.S., Gambill, L., Gao, D., Yaguchi, A., Blenner, M., 2016. Engineering xylose utilization in Yarrowia lipolytica by understanding its cryptic xylose pathway. Biotechnol. Biofuels 9 (1), 149.

Schultz, J.C., Cao, M., Zhao, H., 2019. Development of a CRISPR/Cas9 system for high efficiency multiplexed gene deletion in Rhodospirillum toruloides. Biotechnol. Bioeng. 114 (7), 1521–1530.

Schwarz, C.M., Hussain, M.S., Blenner, M., Wheelond, I., 2016. Synthetic RNA polymerase III promoters facilitate high-efficiency CRISPR-cas9-mediated genome editing in Yarrowia lipolytica. ACS Synth. Biol. 5 (4), 356–359.

Shapiro, R.S., Chavez, A., Porter, C.B.M., Hamblin, M., Kaas, C.S., DiCarlo, J.E., Zeng, G., Xu, X., Revotovich, A.V., Kirienko, N.V., Wang, Y., Church, G.M., Collins, J.J., 2018. A CRISPR-Cas9-based gene drive platform for genetic interaction analysis in Candida albicans. Nat. Microbiol. 3 (1), 73–82.

Sharpe, P.L., Rick, W.Y., Zhu, Q.Q., 2014. Carotenoid Production in a Recombinant Oleaginous Yeast. United States.

Si, T., Chao, R., Min, Y., Wu, Y., Ren, W., Zhao, H., 2017. Automated multiplex genome-scale engineering in yeast. Nat. Commun. 8, 15187.

Spagnoletto, M., Shabbir Hussain, M., Gambill, L., Blenner, M., 2018. Alternative substrate metabolism in Yarrowia lipolytica. Front. Microbiol. 9, 1077.

Strohknell, I., Saijuldis, F.A., Rybarski, J.R., Finkelstein, J.J., Russell, R., 2018. Kinetic basis for DNA target specificity of CRISPR-cas12a. Mol. Cell 71 (5), 816–824 e613, Thomas, D., Sardin-Kerjan, Y., 1997. Metabolism of sulfur amino acids in Saccharomyces cerevisiae. Microbiol. Mol. Biol. Rev. 61 (4), 503–532.

Viane, J., Tiels, P., Logghe, M., Dewaele, S., Martinet, W., Contreras, R., 2000. MET15 as a visual selection marker for Candida albicans. Yeast 16 (13), 1205–1215.

Vyas, V.K., Barana, M.I., Fink, G.R., 2015. A Candida albicans CRISPR system permits genetic engineering of essential genes and gene families. Sci. Adv. 1 (3), e1500248.

Wagner, J.M., Williams, E.V., Alper, H.S., 2018. Developing a piggyBac transposon system and compatible selection markers for insertional mutagenesis and genome engineering in Yarrowia lipolytica. Biotechnol. J. 13 (5), 1800222.

Wang, L., Zong, Z., Liu, Y., Zheng, M., Li, D., Wang, C., Zheng, F., Madzak, C., Liu, Z., 2019. Metabolic engineering of Yarrowia lipolytica for the biosynthesis of crotonic acid. Bioreour. Technol. 287, 121484.

Weninger, A., Hatzl, A.-M., Schmid, C., Vogl, T., Glieder, A., 2016. Multiplexed CRISPR-Cas9-based genome editing of rhodosporidium toruloides. ACS Synth. Biol. 5 (4), 356–359.