



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

Zhiliang Yang¹, Harley Edwards¹, Peng Xu^{*}

Department of Chemical, Biochemical and Environmental Engineering, University of Maryland Baltimore County, Baltimore, MD, 21250, USA



ARTICLE INFO

Keywords:

Genome editing
CRISPR
Cpf1
crRNA
Yarrowia lipolytica
On-target efficiency

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 sulfide) 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 poly-unsaturated 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,

* Corresponding author.

E-mail address: pengxu@umbc.edu (P. Xu).

¹ The two authors contributed equally to this article.

1997). Compared to *Rodosporidium toruloides*, the low intron density (0.17) in *Y. lipolytica* (Mekouar et al., 2010) allows us to easily modify its endogenous pathway and repurpose lipogenesis for various applications. Genome annotation indicates this yeast contains more than 200 hydrophobic compounds assimilation pathways associated with alkane uptake, lipid oxidation and VFA detoxification (Fickers et al., 2005) et al. This feature makes this yeast a superior host to utilize recalcitrant waste/toxic substrates for eco-friendly production of green chemicals (Liu et al., 2019a,b). Due to its prominent industrial potential, a significant amount of work 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., 2017; 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., 2016; Wong et al., 2017; Holkenbrink et al., 2018; Morse et al., 2018) et al. This genetic toolbox affords us a collection of facile genetic tools for streamlined 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; Jakočiūnas 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; Otopual et al., 2019; Schultz et al., 2019), and oleaginous yeast *Y. lipolytica* (Schwartz et al., 2016; 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 staggered 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 cleavage 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, staggered 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 efficiency 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'-tRNA^{Gly} promoter and the 5sRNA promoter were tested to optimize crRNA expression. Our engineered CRISPR-Cpf1 system has been used to edit two counter-selectable genetic markers, URA3 (encoding orotidine 5'-phosphate decarboxylase) and CAN1 (encoding arginine permease). This system was further applied to edit three visual-selectable genetic markers encoding the sulfur-housekeeping genes (MET2, MET6 and MET25) of *Y. lipolytica*, with high cleavage efficiency. We further performed multiplexed targeting by using a tandem array of three crRNAs for URA3, CAN1 and MET25 and achieved high targeting efficiency for duplex and triplex editing. Taken together, this CRISPR-Cpf1-assisted system provides a highly efficient and versatile toolkit that expanded our capability for genome-targeting and engineering in oleaginous yeast species.

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-canavanine is a structural analog to arginine and will stop polypeptide synthesis if the cell mistakenly takes up canavanine. *CAN1* mutation confers resistance to L-canavanine toxicity, which allows counter-selection of *CAN1* mutants on CSM-Arg agar plates supplemented with L-canavanine. In order to implement the CRISPR-Cpf1 system in *Y. lipolytica*, the AsCpf1 gene was codon-optimized using *homo sapiens* codon usage (Zetsche et al., 2015) and expressed using the strong TEF-intron promoter (Fig. 2A). A nuclear localization signal (NLS) was fused to the C-terminal of AsCpf1 to localize the Cas12/Cpf1 endonuclease to the nucleus. The TEF-intron promoter has been characterized as a strong constitutive promoter and employed to express the sgRNA to implement CRISPR-Cas9 based editing of *CAN1* in *Y. lipolytica* (Wong et al., 2017). We first expressed the crRNA of *CAN1* using this well-characterized TEF-intron promoter. The crRNA sequence was flanked by the hammer head ribozyme (HHR) and hepatitis delta virus (HDV) ribozyme (Bayer and Smolke, 2005; Gao and Zhao, 2014; Gao et al., 2016a,b) to facilitate the release of functional crRNA from primary transcript via self-cleavage of the two ribozymes (Fig. 2B). The CRISPR-Cpf1 mediated DSB was primarily repaired by non-homologous end joining (NHEJ) in *Y. lipolytica*. Colony PCR products were sequenced to identify in-del mutations at the target site. As was shown in Fig. 2D, random insertion or deletion mutations were detected at the crRNA target site downstream of the TTTN PAM in all the canavanine-resistant colonies. Most strikingly, the editing efficiency of *CAN1* in *Y. lipolytica* po1g strain reached 72.9% ± 9.5% (12/16, 13/16,

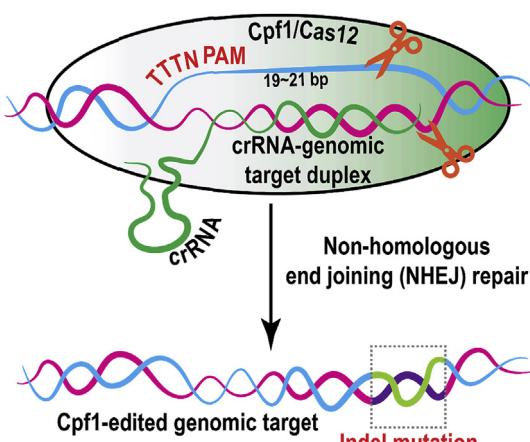


Fig. 1. Crispr-cas12/cpf1 recognizes TTTN protospacer adjacent motif (PAM) and is guided by a simple crRNA without the need for tracrRNA (trans-activating CRISPR RNA). Cpf1 introduces double strand break (DSB) in a staggered pattern and generate sticky ends. The DSB is primarily repaired by non-homologous end joining (NHEJ) in *Y. lipolytica*.

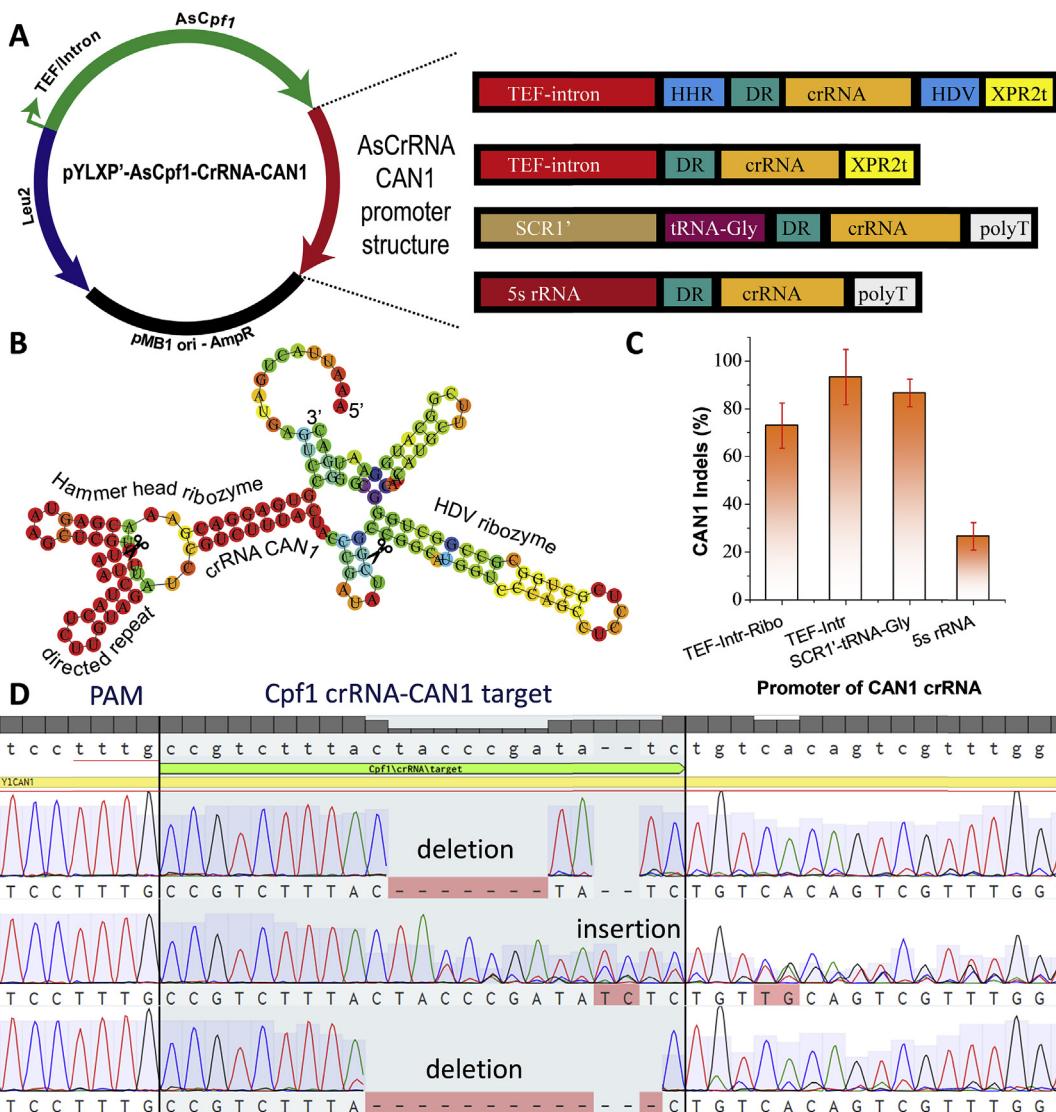


Fig. 2. Crispr-cas12/cpf1-mediated genome-editing of dominant marker arginine permease encoded by *CAN1*. (A) Four genetic configurations of crRNA promoter were tested to drive the expression of crRNA-CAN1. (B) Type II RNA promoter (TEF) were flanked with upstream hammer head ribozyme and downstream 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 \pm sd. (D) Sanger DNA sequencing to validate the on-target insertion or deletion (indels) mutations for *CAN1* loci.

10/16) 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-AsCpf1 system demonstrated superior editing efficiency to introduce in-del mutations in *Y. lipolytica*, and prolonged incubation was not necessary. Potentially, this CRISPR-Cpf1 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'-tRNA^{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 $93.3\% \pm 11.5\%$ (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

(Fonfara et al., 2016; Zetsche et al., 2017). In *Pichia pastoris*, polymerase II promoter P_{HXT} was also recently used for the expression of sgRNA in CRISPR-Cas9 based system recently (Weninger et al., 2016). It was found that direct fusion of the sgRNA to P_{HXT} led to high targeting efficiency.

An editing efficiency of $86.6\% \pm 5.7\%$ (9/10, 9/10, 8/10) was also achieved for *CAN1* targeting using the hybrid $SCR1'$ -tRNA^{Gly} promoter (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 cRNA 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 $SCR1'$ -tRNA^{Gly} 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

$SCR1'$ -tRNA^{Gly} 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 (Strohkendl 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 TTTCs 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 *TRP1* (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.

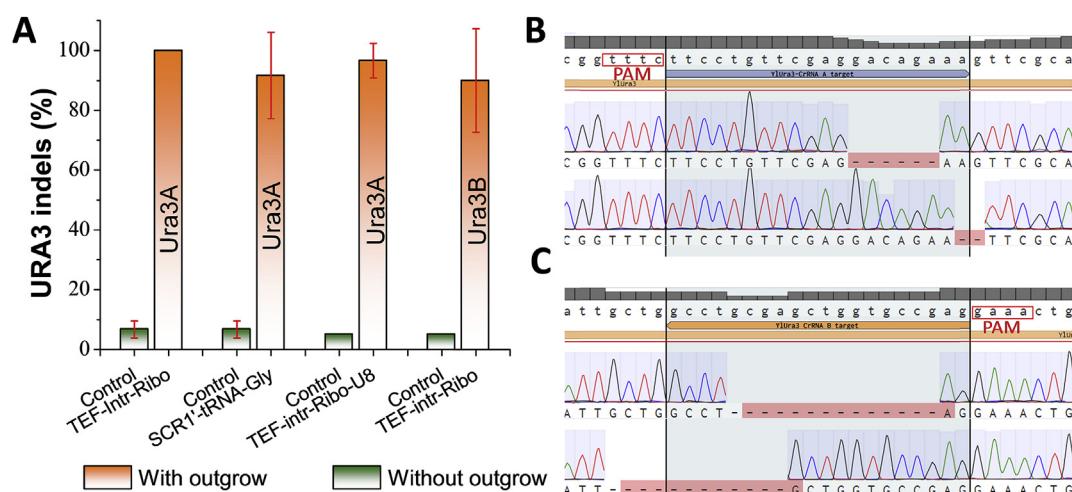


Fig. 3. Crispr-cas12/cpf1-mediated genome-editing of counter-selectable marker orotidine 5'-phosphate decarboxylase encoded by *URA3*. (A) On-target genome-editing efficiency for *URA3* with different crRNA configurations and modifications. $N = 3$, the reported data represents mean \pm sd. (B) Indel mutations of *URA3* genetic marker when the crRNA-*URA3A* targets to the sense strand. (C) Indel mutations of *URA3* genetic marker when the crRNA-*URA3B* targets to the antisense strand.

2.4. CRISPR-Cpf1 mediated in-del mutation of non-dominant markers

The methionine pathway starts with a number of sulfur house-keeping genes that sequentially reduce sulfate (SO_4^{2-}) to sulfite (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 sulfide PbS) if colorless and soluble lead (lead nitrate or lead acetate) salt was supplied to the media. This submissive 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 submissive markers: *MET25* (encoding homocysteine synthase), *MET2* (encoding O-acetyl homoserine synthase) and *MET6* (encoding homocysteine methyltransferase) involved in methionine metabolism (Thomas and Surdin-Kerjan 1997) were targeted. After transforming *Y. lipolytica* P01g with the plasmid pYLPX'-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 pYLPX'-AsCpf1 plasmid. The precipitation of lead sulfide (PbS) and the formation of black colony were found for all these genetic targets, with varying genome-editing efficiency (Fig. 4E). The disruption efficiency for the three *MET6* targets was found to be $75\% \pm 5\%$ (16/20, 14/20, 15/20) for

Met6a, $40\% \pm 5\%$ (8/20, 7/20, 9/20) for *Met6b* and $55\% \pm 5\%$ (10/20, 11/20, 12/20) for *Met6aU8*, respectively (Fig. 4E). The genome-editing efficiency for the two *MET2* targets was found to be $73.3\% \pm 5.7\%$ (8/10, 7/10, 7/10) for *Met2a*, and $53.3\% \pm 5.7\%$ (5/10, 6/10, 5/10) for *Met2b* (Fig. 4E), which is comparable to the editing efficiency obtained from the *MET6* marker. After the black colonies were formed, we further detected the *met6* indel mutations with a T7 endonuclease kit, which allows us to identify heteroduplex DNAs containing any mismatches between the two strands of the complementary DNA. Colony PCR was performed and the PCR products were subjected to denaturation and re-annealing to form the heteroduplex DNA. After digestion with T7 endonuclease, two shorter bands corresponding to the cleavage site of the edited PCR products was observed (Supplementary Fig. S2), indicating that the genome-editing events occurred at the target site of *MET6*. Notably, the varying targeting efficiency of the sulfur metabolism genes highlighted the effect of crRNA guide sequence on gene-editing 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 $83.3\% \pm 5.7\%$ (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

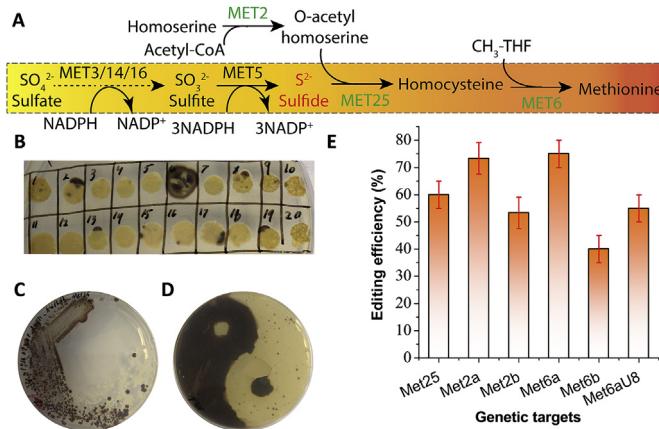


Fig. 4. Crispr-cas12/cpf1-mediated genome-editing of submissive marker encoded by sulfur house-keeping genes *MET25*, *MET6* and *MET2*. (A) Methionine biosynthetic pathway is encoded by a number of reduction steps to incorporate sulfide into the carbon backbone of homoserine. Sulfate was sequentially reduced to sulfide, blocking the sulfide incorporation pathway will result in the accumulation of sulfide (S^{2-}) intracellularly. (B) Agar plate screening of *MET25* indel mutations. Colonies with black sector indicates the successful mutation of *MET25*. (C) Re-streaking of the sectored colonies onto MLA plate to isolate genetically pure *MET25* mutants. (D) A Taichi or Ying-Yang art is created by plating the wild type P01g strain and the *MET25* mutant strains on the MLA plate. (E) On-target genome-editing efficiency for *MET25*, *MET2* and *MET6* with different crRNA configurations and modifications. $N = 3$, the reported data represents mean \pm sd.

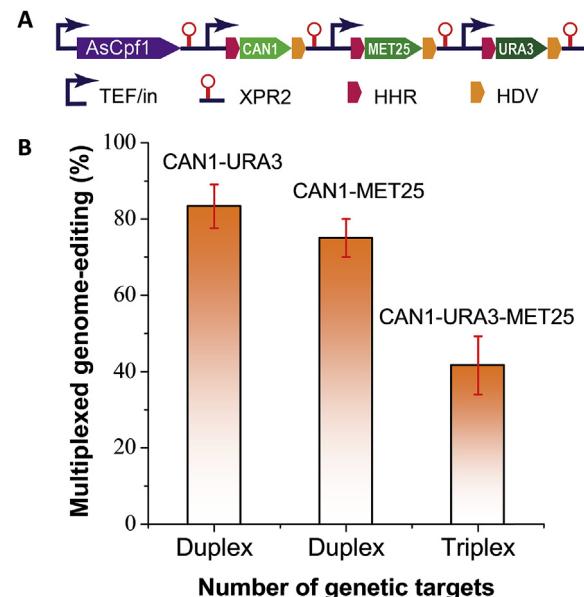


Fig. 5. CRISPR-Cpf1/cas12 mediated multiplexed genome-editing for *MET25*, *URA3* and *CAN1* in *Y. lipolytica*. (A) Genetic configurations for three crRNAs arrays to drive multiple genome-editing targets. A detailed plasmid map for this crRNA array could be found in Supplementary Fig. S3. (B) Duplex genome-editing efficiency for *CAN1-URA3* and *CAN1-MET25*; and triplex genome-editing efficiency for *CAN1-URA3-MET25*.

found to be $75\% \pm 5\%$ (Fig. 5B). It should be noted that the *URA3* genome-editing is enriched with cell outgrow 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 outgrow in uracil-rich media, the genome-edited cells were screened based on 5'-FOA resistance, the formation of black colony and canavanine resistance (Supplementary Fig. S4). We observed that the triplex editing efficiency reached $41.7\% \pm 7.6\%$ (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 simplified crRNA structure without the need of tracrRNA makes Cpf1 a potentially better candidate for genome-editing, offering us an easy-to-operate approach to express crRNAs.

With this toolkit, we have tested the CRISPR-Cpf1 genome editing efficiency for two counter-selectable markers (*URA3* and *CAN1*) and three submissive markers (*MET2*, *MET25* and *MET6*). We have validated genome-editing events (indel mutations) by both DNA sequencing and heteroduplex DNA digestion. To optimize crRNA expression, we also assessed four versions of promoters, ranging from TEF-intron-ribozyme, TEF-intron, tRNA^{Gly} to 5s RNA promoters. Our results demonstrate that TEF-intron promoter alone is sufficient to express crRNAs without ribozymes, possibly due to the RNA-processing ability of AsCpf1. We also observed that modification of crRNAs by adding polyUs downstream of crRNA could facilitate the faster release and maturation of crRNAs from the primary RNA transcripts. For counter-selectable markers (*CAN1* or *URA3*), our CRISPR-Cpf1 editing efficiency was ranging from 72.9% to 96%; for submissive markers (*MET2*, *MET25* and *MET6*), our editing efficiency was ranging from 40% to 80%. For multiplexed genomic targets, our editing efficiency reached 75–83% for duplex targets, and 45% for triplex targets. Taken together, this CRISPR-Cpf1 system should complement the Cas9 toolkit and enable us to precisely edit the genomic targets of *Y. lipolytica* with improved editing efficiency. This work provides us an invaluable tool to perform multiplexed genome-editing and may accelerate our ability to deliver oleaginous yeast cell factories for various applications.

4. Methods and materials

4.1. Strains and growth conditions

E. coli NEB5 α 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-Arg 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) used in this 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 cleaned with Zymoclean kits and Gibson assembled into the SnaB1 and KpnI digested pYLXP', to yield plasmid pYLXP'-AsCpf1. To construct the crRNA for *CAN1* targeting, AvrII-Fwd and Can1-crRR were used to PCR amplify the fragment crRNA-Can1up. Sall_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 pYLXP' digested with AvrII and Sall using Gibson assembly to yield pYLXP'-AscrRNA-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 smaller fragment was gel-recovered and ligated with the *Nhe*I and *Sall* digested pYLXP'-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 pYLXP'-AsCpf1-AscrRNA-Can1 were picked up using sterile pipette tips and spotted on CSM-Arg plates supplemented with 50 mg/L L-canavanine. Colonies of *Y. lipolytica* Po1f Δ ALK7:URA3 transformed with pYLXP'-AsCpf1-AscrRNA-URA3A or pYLXP'-AsCpf1-AscrRNA-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 pYLXP'-AsCpf1-AscrRNA-Met25 were spotted on MLA plates. For *CAN1* or *URA3* editing, incubation of 2–3 days allowed the formation of colonies on CSM-Arg 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 pYLXP'-AsCpf1-AscrRNA-CAN1 to result in pYLXP'-AsCpf1-AscrRNA-CAN1-MET25 and pYLXP'-AsCpf1-AscrRNA-CAN1-URA3A, respectively. The plasmids were transformed into *Y. lipolytica* po1g and po1f Δ ALK7: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 pYLXP'-AsCpf1-AscrRNA-CAN1-MET25 to yield pYLXP'-AsCpf1-AscrRNA-CAN1-MET25-URA3A-U8. This construct was transformed into strain po1f Δ ALK7: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.

Acknowledgements

Dr. Zhiliang Yang was supported by the Bill & Melinda Gates Foundation under grant no. OPP1188443. Harley Edward was supported by National Science Foundation under grant no. 1805139. Dr. Xu would like to thank the helpful discussion and suggestions with Prof. Jef Boeke and the Boeke lab members at NYU Langone Medical School.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.mec.2019.e00112>.

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.

Bailey, R., Madden, K.T., Trueheart, J., 2010. Production of Carotenoids in Oleaginous Yeast and Fungi. United States.

Bao, Z., Xiao, H., Liang, J., Zhang, L., Xiong, X., Sun, N., Si, T., Zhao, H., 2014. Homology-integrated CRISPR–Cas (Hi-CRISPR) system for one-step multigene disruption in *Saccharomyces cerevisiae*. *ACS Synth. Biol.* 4 (5), 585–594.

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.

Bin Moon, S., Lee, J.M., Kang, J.G., Lee, N.E., Ha, D.I., Kim, D.Y., Kim, S.H., Yoo, K., Kim, D., Ko, J.H., Kim, Y.S., 2018. Highly efficient genome editing by CRISPR-Cpf1 using CRISPR RNA with a uridinylate-rich 3'-overhang. *Nat. Commun.* 9 (1), 3651.

Blazeck, J., Hill, A., Jamoussi, M., Pan, A., Miller, J., Alper, H.S., 2015. Metabolic engineering of *Yarrowia lipolytica* for itaconic acid production. *Metab. Eng.* 32, 66–73.

Blazeck, J., Liu, L., Redden, H., Alper, H., 2011. Tuning gene expression in *Yarrowia lipolytica* by a hybrid promoter approach. *Appl. Environ. Microbiol.* 77.

Blazeck, J., Reed, B., Garg, R., Gerstner, R., Pan, A., Agarwala, V., Alper, H.S., 2013. Generalizing a hybrid synthetic promoter approach in *Yarrowia lipolytica*. *Appl. Microbiol. Biotechnol.* 97.

Bordes, F., Fudalej, F., Dossat, V., Nicaud, J.M., Marty, A., 2007. A new recombinant protein expression system for high-throughput screening in the yeast *Yarrowia lipolytica*. *J. Microbiol. Methods* 70 (3), 493–502.

Bredeweg, E.L., Pomraning, K.R., Dai, Z., Nielsen, J., Kerkhoven, E.J., Baker, S.E., 2017. A molecular genetic toolbox for *Yarrowia lipolytica*. *Biotechnol. Biofuels* 10.

Celińska, E., Ledesma-Amaro, R., Larroude, M., Rossignol, T., Pauthenier, C., Nicaud, J.-M., 2017. Golden Gate Assembly system dedicated to complex pathway manipulation in *Yarrowia lipolytica*. *Microb. Biotechnol.* 10 (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 indiscriminate single-stranded DNase activity. *Science* 360 (6387), 436.

Cong, L., Ran, F.A., Cox, D., Lin, S., Barretto, R., Habib, N., Hsu, P.D., Wu, X., Jiang, W., Marraffini, L.A., Zhang, F., 2013. Multiplex genome engineering using CRISPR/cas systems. *Science* 339 (6121), 819–823.

Cost, G.J., Boeke, J.D., 1996. A useful colony colour phenotype associated with the yeast selectable/counter-selectable marker MET15. *Yeast* 12 (10), 939–941.

Cui, Z., Gao, C., Li, J., Hou, J., Lin, C.S.K., Qi, Q., 2017. Engineering of unconventional yeast *Yarrowia lipolytica* for efficient succinic acid production from glycerol at low pH. *Metab. Eng.* 42, 126–133.

DiCarlo, J.E., Norville, J.E., Mali, P., Rios, X., Aach, J., Church, G.M., 2013. Genome engineering in *Saccharomyces cerevisiae* using CRISPR-Cas systems. *Nucleic Acids Res.* 41 (7), 4336–4343.

Dimitris, S., Zoe, S., Anna Rapti, P., Seraphim, 2019. Valorization of crude glycerol, residue deriving from biodiesel production process, with the use of wild-type new isolated *Yarrowia lipolytica* strains: production of metabolites with pharmaceutical and biotechnological interest. *Curr. Pharmaceut. Biotechnol.* 20, 1–14.

Fickers, P., Benetti, P.H., Wache, Y., Marty, A., Mauersberger, S., Smit, M.S., Nicaud, J.M., 2005. Hydrophobic substrate utilisation by the yeast *Yarrowia lipolytica*, and its potential applications. *FEMS Yeast Res.* 5 (6–7), 527–543.

Fonfara, I., Richter, H., Bratović, M., Le Rhun, A., Charpentier, E., 2016. The CRISPR-associated DNA-cleaving enzyme Cpf1 also processes precursor CRISPR RNA. *Nature* 532 (7600), 517.

Gaillardin, C., Ribet, A., Heslot, H., 1985. Integrative transformation of the yeast *Yarrowia lipolytica*. *Curr. Genet.* 10 (1), 49–58.

Gao, C., Yang, X., Wang, H., Rivero, C.P., Li, C., Cui, Z., Qi, Q., Lin, C.S.K., 2016a. Robust succinic acid production from crude glycerol using engineered *Yarrowia lipolytica*. *Biotechnol. Biofuels* 9 (1), 179.

Gao, S., Tong, Y., Wen, Z., Zhu, L., Ge, M., Chen, D., Jiang, Y., Yang, S., 2016b. Multiplex gene editing of the *Yarrowia lipolytica* genome using the CRISPR-Cas9 system. *J. Ind. Microbiol. Biotechnol.* 43 (8), 1085–1093.

Gao, S., Tong, Y., Zhu, L., Ge, M., Zhang, Y., Chen, D., Jiang, Y., Yang, S., 2017. Iterative integration of multiple-copy pathway genes in *Yarrowia lipolytica* for heterologous beta-carotene production. *Metab. Eng.* 41.

Gao, Y., Zhao, Y., 2014. Self-processing of ribozyme-flanked RNAs into guide RNAs in vitro and in vivo for CRISPR-mediated genome editing. *J. Integr. Plant Biol.* 56 (4), 343–349.

Holkenbrink, C., Dam, M.I., Kildegård, K.R., Beder, J., Dahlin, J., Domenech Belda, D., Borodina, I., 2018. EasyCloneYALI: CRISPR/Cas9-Based synthetic toolbox for engineering of the yeast *Yarrowia lipolytica*. *Biotechnol. J.* 13 (9), e1700543.

Jakociunas, T., Bonde, I., Herrgård, M., Harrison, S.J., Kristensen, M., Pedersen, L.E., Jensen, M.K., Keasling, J.D., 2015. Multiplex metabolic pathway engineering using CRISPR/Cas9 in *Saccharomyces cerevisiae*. *Metab. Eng.* 28, 213–222.

Jang, I.S., Yu, B.J., Jang, J.Y., Jegal, J., Lee, J.Y., 2018. Improving the efficiency of homologous recombination by chemical and biological approaches in *Yarrowia lipolytica*. *PLoS One* 13 (3), e0194954.

Jiao, X., Zhang, Y., Liu, X., Zhang, Q., Zhang, S., Zhao, Z.K., 2019. Developing a CRISPR/Cas9 system for genome editing in the basidiomycetous yeast *Rhodosporidium toruloides*. *Biotechnol. J.* e1900036.

Jin, C.-C., Zhang, J.-L., Song, H., Cao, Y.-X., 2019. Boosting the biosynthesis of betulinic acid and related triterpenoids in *Yarrowia lipolytica* via multimodular metabolic engineering. *Microb. Cell Factories* 18 (1), 77.

Juretzek, T., Le Dall, M., Mauersberger, S., Gaillardin, C., Barth, G., Nicaud, J., 2001. Vectors for gene expression and amplification in the yeast *Yarrowia lipolytica*. *Yeast* 18 (2), 97–113.

Larroude, M., Celinska, E., Back, A., Thomas, S., Nicaud, J.M., Ledesma-Amaro, R., 2018. A synthetic biology approach to transform *Yarrowia lipolytica* into a competitive biotechnological producer of β-carotene. *Biotechnol. Bioeng.* 115 (2), 464–472.

Ledesma-Amaro, R., Lazar, Z., Rakicza, M., Guo, Z., Fouchard, F., Coq, A.-M.C.-L., Nicaud, J.-M., 2016. Metabolic engineering of *Yarrowia lipolytica* to produce chemicals and fuels from xylose. *Metab. Eng.* 38, 115–124.

Li, H., Alper, H.S., 2016. Enabling xylose utilization in *Yarrowia lipolytica* for lipid production. *Biotechnol. J.* 11 (9), 1230–1240.

Liu, H., Marsafari, M., Deng, L., Xu, P., 2019a. Understanding lipogenesis by dynamically profiling transcriptional activity of lipogenic promoters in *Yarrowia lipolytica*. *Appl. Microbiol. Biotechnol.* 103 (7), 3167–3179.

Liu, H., Marsafari, M., Wang, F., Deng, L., Xu, P., 2019b. Engineering acetyl-CoA metabolic shortcut for eco-friendly production of polyketides triacetic acid lactone in *Yarrowia lipolytica*. *Metab. Eng.* 56, 60–68.

Lv, Y., Edwards, H., Zhou, J., Xu, P., 2019. Combining 26s rDNA and the Cre-loxP system for iterative gene integration and efficient marker curation in *Yarrowia lipolytica*. *ACS Synth. Biol.*

Lv, Y., Koffas, M., Zhou, J., Xu, P., 2019b. Optimizing Oleaginous Yeast Cell Factories for Flavonoids and Hydroxylated Flavonoids Biosynthesis. *bioRxiv*, p. 614099.

Mans, R., van Rossum, H.M., Wijsman, M., Backx, A., Kuijpers, N.G.A., van den Broek, M., Daran-Lapujade, P., Pronk, J.T., van Maris, A.J.A., Daran, J.-M.G., 2015. CRISPR/Cas9: a molecular Swiss army knife for simultaneous introduction of multiple genetic modifications in *Saccharomyces cerevisiae*. *FEMS Yeast Res.* 15 (2).

Markham, K.A., Palmer, C.M., Chwatkow, M., Wagner, J.M., Murray, C., Vazquez, S., Swaminathan, A., Chakravarty, I., Lynd, N.A., Alper, H.S., 2018. Rewiring *Yarrowia lipolytica* toward triacetic acid lactone for materials generation. *Proc. Natl. Acad. Sci.* 115 (9), 2096.

Mekouar, M., Blanc-Lenfle, I., Ozanne, C., Da Silva, C., Cruaud, C., Wincker, P., Gaillardin, C., Neuveglise, C., 2010. Detection and analysis of alternative splicing in *Yarrowia lipolytica* reveal structural constraints facilitating nonsense-mediated decay of intron-retaining transcripts. *Genome Biol.* 11 (6), R65-R65.

Min, K., Ichikawa, Y., Woolford, C.A., Mitchell, A.P., 2016. *Candida albicans* gene deletion with a transient CRISPR-cas9 system. *mSphere* 1 (3).

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., 2017. Dramatic improvement of CRISPR/Cas9 editing in *Candida albicans* by increased single guide RNA expression. *mSphere* 2 (2).

Nicaud, 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.

Otopual, P.B., Ito, M., Arkin, A.P., Magnuson, J.K., Gladden, J.M., Skerker, J.M., 2019. Multiplexed CRISPR-cas9-based genome editing of *rhodospiridium toruloides*. *mSphere* 4 (2) e00099-00019.

Qiao, K., Wasylewko, 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 *Rhodospiridium toruloides*. *Biotechnol. Bioeng.*

Schwartz, C.M., Hussain, M.S., Blenner, M., Wheeldon, 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., Revtovich, 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.

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

Strohkendl, I., Saifuddin, F.A., Rybarski, J.R., Finkelstein, I.J., Russell, R., 2018. Kinetic basis for DNA target specificity of CRISPR-cas12a. *Mol. Cell* 71 (5), 816–824 e813.

Thomas, D., Surdin-Kerjan, Y., 1997. Metabolism of sulfur amino acids in *Saccharomyces cerevisiae*. *Microbiol. Mol. Biol. Rev.* 61 (4), 503–532.

Viaene, 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., Barrasa, 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), 1800022.

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. *Bioresour. Technol.* 287, 121484.

Weninger, A., Hatzl, A.-M., Schmid, C., Vogl, T., Glieder, A., 2016. Combinatorial optimization of CRISPR/Cas9 expression enables precision genome engineering in the methylotrophic yeast *Pichia pastoris*. *J. Biotechnol.* 235, 139–149.

Wong, L., Engel, J., Jin, E., Holdridge, B., Xu, P., 2017. YaliBricks, a versatile genetic toolkit for streamlined and rapid pathway engineering in *Yarrowia lipolytica*. *Metab. Eng. Commun.* 5, 68–77.

Wong, L., Holdridge, B., Engel, J., Xu, P., 2019. Genetic tools for streamlined and accelerated pathway engineering in *Yarrowia lipolytica*. In: Santos, C.N.S., Ajikumar, P.K. (Eds.), *Microbial Metabolic Engineering: Methods and Protocols*. Springer New York, New York, NY, pp. 155–177.

Xie, K., Minkenberg, B., Yang, Y., 2015. Boosting CRISPR/Cas9 multiplex editing capability with the endogenous tRNA-processing system. *Proc. Natl. Acad. Sci.* 112 (11), 3570.

Xu, J., Liu, N., Qiao, K., Vogg, S., Stephanopoulos, G., 2017a. Application of metabolic controls for the maximization of lipid production in semicontinuous fermentation. *Proc. Natl. Acad. Sci.* 114 (27), E5308–E5316.

Xu, P., Qiao, K., Ahn, W.S., Stephanopoulos, G., 2016. Engineering *Yarrowia lipolytica* as a platform for synthesis of drop-in transportation fuels and oleochemicals. *Proc. Natl. Acad. Sci.* 113 (39), 10848–10853.

Xu, P., Qiao, K., Stephanopoulos, G., 2017b. Engineering oxidative stress defense pathways to build a robust lipid production platform in *Yarrowia lipolytica*. *Biotechnol. Bioeng.* 114 (7), 1521–1530.

Zetsche, B., Gootenberg, Jonathan S., Abudayyeh, Omar O., Slaymaker, Ian M., Makarova, Kira S., Essletzbichler, P., Volz, Sara E., Joung, J., van der Oost, J., Regev, A., Koonin, Eugene V., Zhang, F., 2015. Cpf1 is a single RNA-guided endonuclease of a class 2 CRISPR-cas system. *Cell* 163 (3), 759–771.

Zetsche, B., Heidenreich, M., Mohanraj, P., Fedorova, I., Kneppers, J., DeGennaro, E.M., Winblad, N., Choudhury, S.R., Abudayyeh, O.O., Gootenberg, J.S., 2017. Multiplex gene editing by CRISPR-Cpf1 using a single crRNA array. *Nat. Biotechnol.* 35 (1), 31.

Zhang, Y., Wang, J., Wang, Z., Zhang, Y., Shi, S., Nielsen, J., Liu, Z., 2019. A gRNA-rRNA array for CRISPR-Cas9 based rapid multiplexed genome editing in *Saccharomyces cerevisiae*. *Nat. Commun.* 10 (1), 1053.

Zheng, X., Zheng, P., Zhang, K., Cairns, T.C., Meyer, V., Sun, J., Ma, Y., 2018. 5S rRNA promoter for guide RNA expression enabled highly efficient CRISPR/Cas9 genome editing in *Aspergillus Niger*. *ACS Synth. Biol.*