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Production of geranylgeraniol on overexpression of a prenyl diphosphate synthase fusion gene in *Saccharomyces cerevisiae*

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**Running title:** Geranylgeraniol Production by Recombinant Yeast without Sterols
Abstract: An acyclic diterpene alcohol, \((E,E,E)\)-geranylgeraniol (GGOH), is one of the important compounds used as perfume and pharmacological agents. A deficiency of squalene (SQ) synthase activity allows yeasts to accumulate an acyclic sesquiterpene alcohol, \((E,E)\)-farnesol, in their cells. Since sterols are essential for the growth of yeasts, a deficiency of SQ synthase activity makes the addition of supplemental sterols to the culture media necessary. To develop a GGOH production method not requiring any supplemental sterols, we overexpressed \(HMG1\) encoding hydroxymethylglutaryl-CoA reductase and the genes of two prenyl diphosphate synthases, \(ERG20\) and \(BTS1\), in \(Saccharomyces cerevisiae\). A prototrophic diploid coexpressing \(HMG1\) and the \(ERG20\)-\(BTS1\) fusion accumulated GGOH with neither disruption of the SQ synthase gene nor the addition of any supplemental sterols. The GGOH content on the diploid cultivation in a 5 l-jar fermenter reached 138.8 mg/l under the optimal conditions.

KEY WORDS: geranylgeraniol; mevalonate pathway; hydroxymethylglutaryl-CoA reductase; prenyl diphosphate synthase; yeast recombinant
Introduction

An acyclic diterpene alcohol, \((E,E,E)\)-geranylgeraniol (GGOH), is known to be a fragrant constituent of essential oils. It has been used not only as one of the important ingredients in perfumes, but also as a valuable material for the chemical synthesis of pharmacological agents and hydrophobic vitamins such as vitamin A and E (Benford et al. 1999; Hyatt et al. 2002). The diphosphate derivative of GGOH, \((E,E,E)\)-geranylgeranyl diphosphate (GGPP), is a significant intermediate in the early stage of carotenoid biosynthesis, particularly in plant cells. Although there are eight geometric isomers of GGPP as to the combination of the \(E/Z\)-conformation at three carbon-carbon double bonds, only the \((E,E,E)\)-isomer exhibits significant biological activity (Ogura and Koyama 1998). The chemical synthesis of GGOH has been difficult because of the introduction of three \(E\)-double bonds into the isoprenoid structure. Although, in the last few years, the chemical synthesis for \((all-E)\)-prenyl alcohols has been performed with relatively high yields (Negishi et al. 2002; Yu et al. 2005), metabolic engineering still exhibits greater potential as to an efficient production of \((all-E)\)-prenyl alcohols, because living cells accomplish a variety of simultaneous
reactions with specific stereo-specificities. We previously reported that a recombinant
*Saccharomyces cerevisiae* overexpressing the genes encoding the enzymes in the
mevalonate pathway could produce 145.7 mg/l of \((E,E)\)-farnesol (FOH), suggesting the
yeast has phosphatase activity that converts prenyl diphosphates into prenyl alcohols
(Ohto et al. 2009b). But it was unclear whether GGPP could be similarly
dephosphorylated and secreted into the extracellular fraction to be easily extracted with
organic solvent without cell disruption.

In all organisms, GGPP is synthesized through an enzymatic condensation reaction
of allylic diphosphates such as dimethylallyl diphosphate, \((E)\)-geranyl diphosphate and
\((E,E)\)-farnesyl diphosphate (FPP) with isopentenyl diphosphate(s). Since two FPPs are
also head-to-head condensed to produce squalene (SQ), which is an intermediate during
sterol biosynthesis, GGPP biosynthesis would compete with SQ biosynthesis for FPP
(Fig. 1). SQ accumulates intracellularly due to overexpression of a
3-hydroxy-3-methylglutaryl-CoA reductase gene (*HMG1*), this enzyme being one of the
rate-limiting enzymes in the mevalonate pathway (Donald et al. 1997). Chambon *et al.*
reported that a sterol–auxotrophic yeast deficient in the SQ synthase gene could produce
0.74-1.3 mg/l of FOH in a culture (Chambon et al. 1990; Chambon et al. 1991). The
addition of an inhibitor of SQ synthase allowed yeasts to produce FPP and FOH, but not a sufficient amount of GGOH (Bergstrom et al. 1993; Muramatsu et al. 2008b).

Recently, with both SQ synthase and phytoene synthase inhibitors, a carotenoid-producing yeast *Rhodotorula rubra* IFO 0870 could produce 53.7 mg/l of GGOH (Muramatsu et al. 2008b). The overexpression of an isopentenyl diphosphate delta-isomerase gene and a mutated FPP synthase one in *Escherichia coli* led to the accumulation of 0.13 mg/l GGOH in the cells (Ohto et al. 2009a). In the present study, a recombinant yeast overexpressing the genes encoding enzymes involved in the mevalonate pathway led to the production of GGOH without the addition of any supplemental sterols. In particular, the coexpression of *HMG1* and a prenyl diphosphate synthase fusion gene was effective for the production of GGOH by *S. cerevisiae*.

**Materials and Methods**

**Strains**
S. cerevisiae strains A451 (ATCC 200589) was purchased from the ATCC (American Type Culture Collection, Manassas, VA). AURGG101, which comprises A451 bearing AUR1-C, was previously described (Ohto et al. 2009b). YPH499 (ATCC 76625) and YPH500 (ATCC 76626) were purchased from Stratagene (La Jolla, CA).

Construction of YEp expression vectors

YEp (multicopy-type) expression vectors were constructed from pRS vectors (Stratagene) and YES2 (Invitrogen, Carlsbad, CA), as previously reported (Ohto et al. 2009b). The nucleotide sequences of these vectors are available under DDBJ accession No. AB304849-AB304876.

Preparation of episome DNA constructs for overexpression

Using the primer DNA pairs shown in Fig. 2, the farnesyl diphosphate synthase gene (ERG20) and the geranylgeranyl diphosphate synthase gene (BTS1) were amplified by PCR from pT7-ERG20 and pYES-GGPS (Ohto et al. 2009b), respectively, ligated at the
EcoO109I sites to prepare ERG20 and BTS1 fusion genes, and then inserted into pRS435GAP (DDBJ accession No. AB304858) and pRS445GAP (AB304870). The names and nucleotide sequences of the primers are as follows; SacII-BTS1, $^{5'}$TCC CCG CGG ATG GAG GCC AAG ATA GAT$^{3'}$; BTSI-XhoI, $^{5'}$CAA CTC GAG TCA CAA TTC GGA TA GTG$^{3'}$; BTSI-109I, $^{5'}$GCA GGG ACC CCA ATT CGG ATA AGT GGT C$^{3'}$; 109I-BTS1, $^{5'}$GTA GGG TTC TCA GAA AAA GAA ATT AGG AG$^{3'}$; ERG20-109I, $^{5'}$GCA GGG ACC CTT TGC TTC TCT TGT AAA CT$^{3'}$; 109I-ERG20, $^{5'}$GTA GGG TCC TCA GAA AAA GAA ATT AGG AG$^{3'}$; and T7, $^{5'}$TAA TAC GAC TCA CTA TAG GG$^{3'}$. The names of the resultant episome DNAs harboring the fusion genes are shown in Fig. 2. The episome DNAs for overexpression of other wild type genes were described previously (Ohto et al. 2009b).

Culture conditions for episome DNA-harboring yeasts

The transformants with episome DNAs were selected on agar plates of SD medium (BIO101, Vista, CA) lacking the specified amino acids as to the auxotrophic markers at 30ºC. They were cultivated in 2.5 ml aliquots of YM7 or YMO medium in glass tubes.
by rotary shaking at 130 rpm at 30°C. YM7 medium comprises the YM broth (Becton, Dickinson and Company, Franklin Lakes, NJ) adjusted to pH 7.0 with NaOH, and YMO comprises YM7 including 3.0% (w/v) soybean oil (Nacalai Tesque, Kyoto, Japan).

Construction of a diploid recombinant strain

DNA fragments of the ADE2, HIS3, LYS1 and URA3 coding regions were prepared by PCR from YPH499 genomic DNA based on the sequence in the S. cerevisiae genome database. The ADE2 and HIS3 fragments were introduced into YPH499-originating recombinants using a medium lacking adenine and histidine, and the LYS1 and URA3 fragments were introduced into YPH500 using a medium lacking lysine and uracil. The resultant YPH499 recombinant bearing ADE2 and HIS3, named YPH499-AH, and the YPH500 one bearing LYS1 and URA3, named YPH500-KU, were mated on a minimum SD plate to produce diploid prototrophs.

Preparation of DNA, RNA and crude enzyme
The yeast transformants were cultivated in 100 ml aliquots of SD or SG medium and then cultured in 300-ml Erlenmeyer flasks at 26°C with reciprocal shaking at 120 times/min. The cultivation was finished when OD$_{600}$ reached around 3-4 (corresponding to 23-53 hours), followed by the preparation of DNA, RNA and a crude enzyme solution. The yeast genomic DNA and total RNA were prepared according to the standard procedures. For the preparation of crude enzyme solutions, cells were harvested by centrifugation, disrupted at 4°C with glass beads and then suspended in sterilized water. Each suspension was centrifuged at 12,000 rpm at 4°C for 10 min, and the resultant supernatant was used for the enzyme assay. Protein concentrations were determined with Protein Assay (Bio-Rad, Hercules, CA).

Northern blot hybridization

Probes for Northern blot hybridization were prepared with a PCR DIG Probe Synthesis Kit (Roche Diagnostics, Mannheim Germany) using the templates and primer pairs listed in Table 1. The templates for pT7ERG20, pYESGGPS, and pYHMG1 were described previously (Ohto et al. 2009b). As a control probe, the coding region of the
α-tubulin gene, *TUB1*, was amplified from YPH499 genomic DNA and prepared as a DIG-labeled probe in the same way. Five mg of yeast total RNA per lane was subjected to electrophoresis on a formaldehyde-denatured agarose gel, followed by transfer to a Hybond N nylon membrane (GE Healthcare Ltd, Amersham Place, UK), and cross-linked to it according to a conventional method. Northern blot hybridization was carried out with 100 ng/ml probe DNA at 50°C for 24 hours according to the standard protocol for a DIG Easy Hyb Kit (Roche Diagnostics). The signals were detected as chemiluminescence using a DIG Luminescent Detection Kit (Roche), followed by exposure of the blot to X-ray film.

Prenyl alcohol production in a jar fermenter

The yeast transformants were inoculated from slants into 200 ml aliquots of DOB-based selection medium (BIO101) in 500-ml Erlenmeyer flasks with baffle plates, and cultured at 30°C for 30 hours with shaking at 120 rpm. Ten ml of the resultant culture was inoculated into 5 l of medium comprising 300 g of glucose, 100 g of yeast extract, 100 g of bactopeptone, 550 g of soybean oil, and 5 ml of Adekanol LG109 (Adeka,
Tokyo Japan). The operational conditions were as previously given (Ohto et al. 2009b).

Two milliliters of the culture broth was periodically taken, and the concentrations of glucose, ethanol and acetate were determined as previously reported (Muramatsu et al. 2008b). Cell density was measured by directly counting cells in diluted broth on a hematoplate under a phase-constant microscope.

Extraction of prenyl alcohols and GC/MS analysis

2.5 ml of methanol was added to 2.5 ml of a main culture, followed by thorough mixing. Five ml of pentane was added to the mixture, followed by vigorous agitation. After standing for a few minutes, the pentane layer was transferred to a new glass tube for analysis by GC/MS (Ohto et al. 2009b).

Results

Prenyl alcohol production by the recombinants overexpressing the genes of the enzymes
in the mevalonate and prenyl diphosphate pathways under the control of the TDH3 promoter

In order to determine the effects of genes related with the mevalonate and prenyl diphosphate biosynthesis for GGOH production, each gene was introduced individually into S. cerevisiae YPH499 by means of pRS434GAP (AB304854) and pRS435GAP (AB304858), which were YEp vectors bearing the TDH3 promoter that is constitutively active. Although pRS434GAP was used for the expression of HMG1 and pRS435GAP for other genes, these vectors have almost the same sequences except for the selection marker (TRP1 and LEU2, respectively). Pronounced FOH production was observed on the overexpression of HMG1 among the nine genes responsible for prenyl alcohol production, whereas GGOH increased in amount on overexpression of BTS1, HMG1 and ERG20, in that order (Fig. 3). The YEp vector elevated the productivity of GGOH 5-fold compared with the YIp vector (data not shown).

Overexpression of a ERG20 and BTS1 fusion gene
The PCR fragments of *ERG20*, *BTS1*, the *BTS1-ERG20* fusion gene and the
*ERG20-BTS1* fusion gene were inserted into the multiple cloning sites of the YEp vector
of pRS435, which is located between the *TDH3* promoter and the *CYC1* terminator, to
prepare pRS435GAP-ERG20, pRS435GAP-BTS1 pRS435GGF and pRS435FGG,
respectively, followed by transformation into *S. cerevisiae* YPH499. As shown in Fig. 2,
the two-amino acid linker sequence of Gly-Ser between the two prenyl diphosphate
synthases was designed for the fusion of their enzymes. The fusion genes are supposed
to lead the formation of a fused protein comprised of the BTS1 and the ERG20.
Although the host strain and the recombinant pRS435GAP-ERG20/YPH499 produced
little GGOH in the culture broth, the overexpression of *BTS1* was an effective means of
enhancing GGOH production. This effect was remarkably observed on fusion with the
*ERG20* gene synergistically, being particularly higher, eight-fold, on fusion with *ERG20*
at 6 bp downstream from *BTS1* (pRS435GGF) compared with *BTS1* alone
(pRS435GAP-BTS1 in Fig. 4).
We further introduced this effective episome of pRS435GGF for GGOH production
into SQ-overproducing strain pRS435GAP-HMG1/YPH499 (Ohto et al. 2009b). The
expression of the *BTS1-ERG20* fusion gene and *HMG1* was confirmed by Northern blot
hybridization, where the probe hybridizing to the α-tubulin gene, \textit{TUB1}, was used as a control (Fig. 5). Using the probes of \textit{ERG20} and \textit{BTS1}, strong signals of 3.1 kb were detected for pRS435GGF/YPH499 and pRS435GGF/pRS434GAP-HMG1/YPH499 harboring the \textit{BTS1-ERG20} fusion gene. \textit{HMG1} was also confirmed to be overexpressed in the recombinants having pRS434GAP-HMG1. With YPH499 as the host strain, considerably strong \textit{ERG20} expression was observed but a \textit{BTS1} transcript was not detected. The recombinant overexpressing three effective components (\textit{BTS1}, \textit{ERG20}, and \textit{HMG1}) was used as a promising producer for GGOH production in a jar fermenter.

Jar fermenter production

Prototrophic cells generally exhibit tolerance to environmental stresses such as osmotic pressure, alcohol and other chemical compounds.

pRS435GGF/pRS434GAP-HMG1/YPH499 was transformed with supplementary genes (\textit{ADE2} and \textit{HIS3}) and then mated with YPH500-KU bearing \textit{LYS1} and \textit{URA3} to generate a prototroph diploid of pRS435GGF/pYESHMG044/YPH501-AHKU.
designated as the GGOH strain. The important factors (cell growth rate in the logarithmic phase and cell density in the stationary phase) for the commercial production of GGOH improved with the disappearance of each nutrient requirement marker (data not shown). As the GGOH strain showed the best GGOH production (8.3 mg/l) in a test tube containing YMO medium, it was cultivated in a 5 l-jar fermenter with sufficient aeration and glucose as a carbon source for GGOH production (Fig. 6). After prolonged fermentation for 133.5 h, the GGOH and SQ production reached 138.8 mg/l and 60.0 mg/l, respectively. Other prenyl alcohol production was negligible during the whole fermentation. The FOH production reached a maximal level of 2.09 mg/l at 61.5 h, and gradually decreased thereafter.

Discussion

Having three carbon atoms yielding sixteen geometrical isomers, time-consuming purification steps are inevitable for the chemical synthesis of GGOH. In contrast, for short-chain prenyl diphosphates having not more than 20 carbon atoms, organisms are
able to synthesize all-E isomers through type I prenyl transferases (Ogura and Koyama 1998). Hence, we anticipated that a fermentation process comprising the synthesis of all-E prenyl diphosphate isomers would be highly advantageous for chemical synthesis, especially for that of geranylgeranyl diphosphate, which has four carbon-carbon double bonds. Although the metabolic pathway for GGPP has been revealed in various organisms (Fig. 1), it has so far been difficult to establish overproduction technology based on biochemical pathways (Barkovich and Liao 2001; Ohto et al. 2009a). The low activity of GGPP synthase in S. cerevisiae is a crucial problem for GGOH production, because GGPP is supposed to be utilized only as an isoprenoid moiety of geranylgeranylated proteins, and FPP, one of the substrates for GGPP synthase, is converted into various compounds, mainly into SQ (Fig. 1).

Co-overexpression of BTS1 in the YIp vector and HMG1 in the YEp vector for GGOH overproduction was ineffective compared to the overexpression of HMG1 in the YEp vector in S. cerevisiae A451 for FOH overproduction, as previously reported (Ohto et al. 2009b). Then, we introduced all mevalonate pathway and the prenyl diphosphate pathway-related genes into YEp expression vectors that are maintained as multicopy vectors. Overexpression of BTS1 and HMG1 resulted in more effective production of
GGOH, and the YEp vector proved to be superior to the YIp vector for GGOH production (Fig. 3). It was interesting that the overexpression of ERG20 would be the third significant factor for GGOH production, regardless of the high level expression in wild type cells. The enzyme encoded by BTS1 catalyzes the condensation of FPP and isopentenyl diphosphate into GGPP, but is incapable of utilizing C5-allylic diphosphate substrates (Jiang et al. 1995). A supply of FPP depending upon the expression of ERG20 must be inevitable for GGOH overproduction.

It was reported that type I prenyl diphosphate synthases retain sufficient activity as fusion proteins with maltose binding protein and glutathione S-transferase (Ohto et al. 1998). Based on this information, we designed fusions of ERG20 and BTS1, and found that the overexpression of the BTS1-ERG20 fusion gene was the most effective among the single or fused genes of prenyl diphosphate synthases we had tested (Fig. 4). Before this study, some natural fused genes had been known for diterpenoid biosynthesis. In the first stage of carotenoid biosynthesis, it was reported that a single gene coded for a protein with both activities of prephytoene diphosphate synthase and phytoene synthase (Velayos et al. 2000). The formation of a gibberellic acid skeleton in fungi is achieved through a bifunctional diterpene cyclase comprising two domains, ent-copalyl
diphosphate synthase responsible for cyclization of GGPP and ent-kaurene synthase (Kawaide 2006). Moreover, there has been an attempt to produce capsidiol using an artificial fusion gene of FPP synthase and sesquiterpene cyclase. The amount of epi-aristolochene produced by the fused enzyme was considerably higher than that by a mixture of the two wild type enzymes (Brodelius 2002). The present data also show that the fused enzyme, which is involved in more than two successive enzymatic reactions in a metabolic pathway, enhances the production of hydrophobic compounds in an aqueous environment. The adjacency of two active sites would be convenient for preventing the first product from diffusing into the aqueous solution as small particles before the next enzymatic reaction, and the fused protein might be more stable in the recombinant strain.

Because of the ability of soybean oil to improve prenyl alcohol productivity (Muramatsu et al. 2008a), we cultivated the diploid prototroph bearing HMG1 and the BTS1-ERG20 fusion gene in the optimized medium. A diploid prototroph are commercially attractive for a high growth rate shortening the cultivation period, alcohol tolerant, and broad selectivity as to medium, leading to a low cost. The maximal production of GGOH here (138.8 mg/l) is a significant value compared with other
terpenoids produced by recombinants, such as limonene (5 mg/l), taxadiene (1.3 mg/l), and lycopene (22 mg/l) (Carter et al. 2003; Huang et al. 2001; Kim and Keasling 2001).

This is the first report on the overproduction of GGOH by a microorganism. It had so far been difficult to overproduce hydrophobic terpenoids including GGOH with metabolically-engineered microorganisms. However, the prospects are bright because the fusion gene of BTS1-ERG20 showed such impressive ability. Further investigation of the on expression of other genes involved in the mevalonate and prenyl diphosphate pathways is necessary, and the difference between multi-copy genome integration and episome retention has to be elucidated for the improvement of GGOH production.

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Figure legends

**Fig. 1** Isoprenoids biosynthesis pathway. Black arrows indicate the sequence of enzyme reactions. The corresponding genes were cloned from *S. cerevisiae* and overexpressed in this study. The MEP (methylerythritol phosphate) pathway and the mevalonate pathway are known for isopentenyl diphosphate (C5 isoprenoid) synthesis. The MEP pathway is a prokaryotic pathway in bacteria and some unicellular eukaryotes. The mevalonate pathway is the only route to C5 isoprenoid in animals, plants (except plastids), archaea and fungi including *S. cerevisiae*. FPP, *(E,E)*-farnesyl diphosphate; FOH, *(E,E)*-farnesol; NOH; *(E)*-nerolidol; GGPP, *(E,E,E)*-geranylgeranyl diphosphate; GGOH, *(E,E,E)*-geranylgeraniol.

**Fig. 2** Typical constructs of prenyl diphosphate synthase and those fusion genes. *ERG20* and *BTS1* were fused at the *EcoO109I* site added by means of PCR with primers (gray triangles), and then inserted into the pRS435GAP expression vector. *ERG20*, farnesyl diphosphate synthase gene; *BTS1*, geranylgeranyl diphosphate synthase gene; GS, glycine-serine residues.
**Fig. 3** FOH and GGOH production by recombinants overexpressing genes in the mevalonate and prenyl diphosphate pathways. The FOH (A) and GGOH (B) production by the recombinants of the YPH499 strain overexpressing *HMG1* and other genes with pRS435GAP. The enzyme genes (*ERG10, HMGS, HMG1, ERG12, ERG8, IDI1, ERG20* and *BTS1*) correspond to those in Fig. 1. WILD indicates the YPH499 wild type as a control strain. The recombinants were cultivated in glass tubes containing 2.5 ml of YM7 medium with shaking (130 rpm) at 30°C for 7 days.

**Fig. 4** GGOH production by recombinants. The recombinants were cultivated in glass tubes containing 2.5 ml of YM7 medium with shaking (130 rpm) at 30°C for 7 days. YPH499, host strain; *ERG20*, pRS435GAP-ERG20/YPH499; *BTS1*, pRS435GAP-BTS1/YPH499; FGG, pRS435FGG/YPH400; GGF, pRS435GGF/YPH499.

**Fig. 5** Northern blot hybridization. In each panel the four lanes contain YPH499 wild type (-), pRS435GGF/YPH499 (GGF), pRS434GAP-HMG1/YPH499 (HMG1, -), and pRS435GGF/pRS434GAP-HMG1/YPH499 (HMG1, GGF). The sizes of fragments
were determined with RNA ladder marker (Nippon Gene, Tokyo, Japan). The recombinants were cultivated in glass tubes containing 2.5 ml of YM7 medium with shaking (130 rpm) at 30°C for 3 days.

Fig. 6 Five 1-jar fermenter cultivation of the GGOH strain.

The culture conditions are given under Materials and Methods.
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<td>HMG1(1267-1293)</td>
<td>HMG1(2766-2740)</td>
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<sup>a</sup> BTS1(1-21), 5'ATG GAG GCC AAG ATA GAT GAG<sup>3''</sup>; HMG1(1267-1293), 5' AAC TTT GGT GCA AAT TGG GTC AAT GAT<sup>3''</sup>; SCFPS1, 5' ATG GCT TCA GAA AAA GAA ATT AG<sup>3''</sup>.

<sup>b</sup> BTS1(1008-982), 5'TCA CAA TTC GGA TAA GTG GTC<sup>3''</sup>; HMG1(2766-2740), 5’TCC TAA TGC CAA GAA AAC AGC TGT CAC<sup>3''</sup>; SCFPS2, 5’ CTA TTT GCT TCT CTT GTA AAC TT<sup>3''</sup>. 
The image represents the **Prenyl diphosphate pathway** and **Mevalonate pathway**. The pathways are connected through the enzyme **ERG10** (acetyl-CoA acetyltransferase) and **HMGS** (HMG-CoA synthase). The main products include **ergosterol**, **squalene**, **ubiquinones, menaquinones**, **dolichols**, **farnesylated proteins**, **carotenoids**, and **geranylgeranylated proteins**.

**Mevalonate pathway** involves the following enzymes:
- **HMGS** (HMG-CoA synthase)
- **HMG1** (HMG-CoA reductase)
- **ERG8** (mevalonate kinase)
- **ERG12** (phosphomevalonate kinase)
- **ERG19** (diphosphomevalonate kinase)
- **IDI1** (IPP isomerase)
- **ERG20** (farnesyl diphosphate synthase)

**Prenyl diphosphate pathway** includes:
- **FOH, NOH**
- **GGOH**

**Fig. 1, Ohto et al.**
Fig. 2 Ohto et al.
Fig. 3 Ohto et al.
Fig. 4  Ohto et al.

GGOH production (mg/l)
Fig. 5 Ohto et al.
Fig. 6 Ohto et al.