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Production of Tryptophan by the bacterium *Escherichia coli*

Abstract

This invention is concerned with the production of L-tryptophan by strains of *Escherichia coli*.

5 The invention provides a host and method for growing that host such that plasmids can be stably maintained in the absence of antibiotics, leading to high productivity of tryptophan in fermentation. It offers significant improvements over previous methods and produces tryptophan free from any contamination by tyrosine and phenylalanine thus simplifying downstream processing.

10 The *E. coli* strains having productivity for L-tryptophan comprise in their genome a mutant gene encoding a partially defective tryptophanyl-tRNA synthetase introducing a temperature-conditional tryptophan auxotrophy in the host and further mutations on the chromosome which disable the transport systems encoded by *aroP*, *mtr* and *tnaB* and being transformed with a plasmid containing a tryptophan operon encoding anthranilate
15 synthase freed from feedback-inhibition by tryptophan.

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Invention Title:

Production of Tryptophan by the bacterium Escherichia coli

The following statement is a full description of this invention, including the best method of performing it known to me/us:-

Production of Tryptophan by the bacterium *Escherichia coli*

1. Background of the Invention

This invention is concerned with the production of tryptophan by the bacterium *Escherichia coli*.

5 The invention provides a host and method for growing that host such that plasmids can be stably maintained in the absence of antibiotics, leading to high productivity of tryptophan in fermentation. It offers significant improvements over previous methods and produces tryptophan free from any contamination by tyrosine and phenylalanine thus simplifying downstream processing.

10 2. Brief Description of the Prior Art

There are now numerous examples of the genetic manipulation of microorganisms to make strains that efficiently overproduce particular amino acids.

It is generally accepted in the Art that it is necessary to interfere with normal regulatory circuits that control the expression of genes for biosynthetic pathways, to select
15 mutants whose enzymes are no longer subject to feedback inhibition, and to disable any enzymes which break down the desired product, if any success is to be obtained with the production of particular amino acids. It has also been found useful to increase the copy numbers of certain biosynthetic genes in the cell by introducing into the cell additional gene copies on plasmids. These general principles may be found in Tribe, D.E. and J.
20 Pittard. (1979). **Appl. Environ. Microbiol.** **38**: 181-190, in particular as they relate to tryptophan production.

The significance of feedback inhibition of the first enzymes in the aromatic pathway (the DAHP synthases) and of the first enzyme in the terminal tryptophan pathway, and the need to abolish inhibition, is demonstrated there too.

25 Similarly, it has long been known that it is necessary to inactivate the *trpR* repressor protein which represses the expression of the genes of the tryptophan operon. This is discussed in the above-mentioned publication.

In the case of the tryptophan genes in *E. coli* there is a second system of control called attenuation. Even in *trpR* cells, tryptophan or, more specifically, charged
30 tryptophanyl-tRNA controls expression of the tryptophan operon. When charged tryptophanyl-tRNA is present in excess, transcription of the mRNA for the *trp* operon genes terminates before reaching the sequences coding for the biosynthetic enzymes in about nine of every ten transcripts (Yanofsky, C. (1981)). **Nature** (London) **289**: 751-758). This premature termination of transcription can be prevented by various genetic
35 manipulations such as cloning the *trp* genes after a heterologous promoter or by deleting the attenuator locus. Tribe and Pittard (**Appl. Environ. Microbiol.** (1979). **38**: 181-190) reported a different strategy to overcome attenuation in which they used a mutant that contained a partially defective tryptophanyl-tRNA synthetase enzyme.

When plasmids containing the structural genes for the trp operon are introduced into a cell in which the expression of these trp genes is no longer controlled and in the absence of any strong selection for the plasmid-encoded functions, subsequent multiplication of that cell and its progeny frequently results in plasmid loss from the population. If the original host is a tryptophan prototroph, cells which have lost the plasmid grow more rapidly than cells which retain it, as also do cells in which genetic events (such as deletions or insertions) have reduced or prevented expression of the trp genes present on the plasmid. Over a number of generations, such defective cells (segregants and mutants) become the predominant members of the population and if this population is the basis for a fermentation, the fermentation fails.

Various strategies have been advanced for stabilising plasmid inheritance. A method frequently used is to include a gene for antibiotic resistance on the plasmid and to add antibiotics to the fermentation broth. This method, is however, costly and may provide an environmental hazard. Strategies using a host defective in the biosynthesis of some compound required for growth, together with a plasmid carrying a gene complementing the mutant defect, have been used previously (for example in US 4 371 614), but segregants can accumulate as they continue to synthesise the nutrient for several generations (phenotypic lag). Where the requirement is the same as the nutrient being accumulated, segregants may also be fed by the nutrient which has been accumulated. A limited improvement has been achieved using hosts defective in transport, but this was achieved only under conditions where tryptophan in the medium was low (Imanaka, Patent Disclosure A No. 3-43074).

A need continues to exist for microorganisms capable of producing high levels of tryptophan. Connected is the need for a method to stabilise plasmid inheritance in said microorganisms.

3. Summary of the Invention

These and other objectives of the invention which will hereinafter become more readily apparent have been attained by providing: *E. coli* K-12 strains having productivity for tryptophan and comprising in their genome a mutant gene encoding a partially defective tryptophanyl-tRNA synthetase, introducing a temperature-conditional tryptophan auxotrophy in the host and further mutations on the chromosome which disable the transport systems encoded by *aroP*, *mtr* and *tnaB*, such strains containing a *trpE* allele encoding anthranilate synthase resistance to feedback-inhibition at high concentrations of tryptophan.



Another objective of the invention has been attained by providing a method for producing L-tryptophan by fermentation which comprises culturing a bacterium as described hereinbefore under differing growth and production conditions, and recovering L-tryptophan produced from the culture medium.

5 Accordingly, there is provided according to a first embodiment of the invention an *E. coli* strain having increased productivity for L-tryptophan, said strain comprising a genome having a mutant *trpS* gene encoding a defective tryptophanyl-tRNA synthetase, said synthetase being characterized by a temperature-dependent tryptophan auxotrophy and selected at 27°-30°C., and said strain having a further mutation in at least one gene
10 selected from the group consisting of *mtr*, *aroP*, *tnaA* and *tnaB*, thereby rendering the strain defective in tryptophan transport.

There is provided according to a second embodiment of the invention a method for stabilizing the characteristics of an *E. coli* strain having productivity for L-tryptophan during the growth of inoculum, said method comprising the steps of:

15 introducing into the genome of said *E. coli* strain a mutant gene encoding a partially defective tryptophanyl-tRNA synthetase, said synthetase being characterised by a temperature dependent tryptophan auxotrophy and selected at 27°-30°C.;

introducing at least one further mutation in the genes of *aroP*, *mtr*, *tnaA* or *tnaB*;
and

20 cultivating said strain at 27°-30°C°.

There is provided according to a third embodiment of the invention a method of producing L-tryptophan by fermentation which comprises:

cultivating an *E. coli* strain according to first embodiment of the invention, in an appropriate culture medium at about 30°C., limiting growth by adjusting the
25 concentration of available phosphate;

fermenting said medium at a temperature in the range of about 33°C. to 37°C., in the absence of yeast extract; and

recovering tryptophan accumulated in the culture medium.



Description of the Drawings

Figure 1: Growth rates of JP7847 (*trpS*⁺) and JP6006 (*trpS378*) at 30°C as a function of the concentration of tryptophan in the medium. The medium is half-strength buffer 56 (Monod, J., G. Cohen-Bazire and M. Cohen (1951). **Biochimica et Biophysica Acta** 1: 585-599) supplemented with thiamine at 10µg/mL and glucose at 0.2%). Both strains are tryptophan auxotrophs because of the deletion $\Delta trpLE1413$ and both are defective in the active uptake of tryptophan because of the mutation *mtr-24*, *tna-1* and *aroP519*. They are both in addition, *sac*⁺ *aroF363* *aroG103(FBR)* *trpR363* *tyrR366*.

Figure 2: Stability and productivity of a tryptophan producing strain (JP6015/pMU91) when grown in flasks at different temperatures.

Figure 3: Stability and productivity of a tryptophan producing strain (JP6015/pMU91) when grown in flasks at 30°C in the presence of different concentrations of yeast extract.

Figure 4: A comparison of the sensitivity to feedback-inhibition *in vitro* of anthranilate synthase enzymes from a strain with a wild-type *trpE* allele (JP6768/pMU3018), and strains with mutations *trpE476* (JP6768/pMU3019) and *trpE483* (JP6768/pMU3025).

Figure 5: Growth curves at 42°C of an *aroB*⁺ *trpS*⁺ strain (JP8820) in minimal medium and an *aroB*⁺ *trpS378* strain (JP1451) in minimal medium supplemented with various levels of tryptophan.

Figure 6: Restriction maps of pMU3018 (Figure 6a), pMU3019 (Figure 6b) and pMU3025 (Figure 6c). In each case the vector (pMU578) is shown in black. pMU3019 was constructed similarly to pMU3018, using a 2.9kb *SmaI/HindIII* fragment containing the 5' end of the *trp* operon, but with *trpE476* rather than *trpE* wild type. pMU3025 was derived from pMU3018 by mutagenesis as described in Example 2.

Figure 7: The incorporation of *trpE483* into the *trp* operon.

Figure 8: Restriction map of pMU3028. The vector (pLG339) is shown in black. Constructed in a 2-step cloning: (i) a 2.6kb fragment carrying *serA*⁺ was cloned into the *SmaI* site of pLG339; (ii) an 8.1kb *SalI* fragment carrying *trpE483DCBA* from pMU3027 (See Figure 7) was cloned into the *XhoI* site of the resulting plasmid.

Figure 9: Restriction map of pMU91.

4. Detailed Description of the Invention

The present invention provides a process for high levels of L-tryptophan production by fermentation employing strains of *E. coli* K-12.

These strains having productivity for L-tryptophan comprise in their genome a mutant gene encoding a partially defective tryptophanyl-tRNA synthetase introducing a temperature-conditional tryptophan auxotrophy in the host and further mutations on the chromosome which disable the transport systems encoded by *aroP*, *mtr* and *tnaB* and being transformed with a plasmid containing a tryptophan operon encoding anthranilate synthase freed from feedback-inhibition by tryptophan.

As described in section 2, there exists a problem with strains overproducing a particular nutrient, where maintenance of stability is dependent only upon the host having a requirement for the over-produced nutrient, as segregants will continue to grow, firstly because of phenotypic lag and secondly, because they will readily be fed by the nutrient that has accumulated. Even if the host strain is defective in the active transport of the nutrient, the selection will only succeed when the nutrient concentration is relatively low. As is shown in Figure 1, at levels of tryptophan such as 1mM or greater, a tryptophan auxotroph unable to actively transport tryptophan nevertheless grows with a normal doubling time. This tryptophan concentration of 1mM or about 0.2g/L will be quickly reached when a tryptophan-producing strain is grown and hence the selection for plasmid stability will be rapidly lost under production conditions.

We have discovered that *trp*⁻ strains with a mutation especially such as *trpS378*, which partially inactivates the tryptophanyl-tRNA synthetase enzyme, require very high concentrations of tryptophan within the cell. Figure 1 shows that, the transport negative mutant also carries this *trpS378* mutation, it requires at least 5mM tryptophan for good growth to occur, even at 30°C. This means that until the tryptophan concentration in the medium reaches 1g/L any segregants produced by plasmid loss will be at a growth disadvantage. This requirement for very high tryptophan concentrations before segregants compete well in growth is a significant improvement as it maintains selection for retention of the plasmid not only during growth of the inoculum, but also throughout most of the growth phase during the final fermentation. This combination of transport-negative mutations and especially *trpS378* significantly enhances tryptophan yields when compared with *trpS*⁺ transport-negative combinations. Said mutations preferably disable the transport systems encoded by *aroP*, *mtr* and *tnaB*. Typical strains include but are not limited to strains containing the mutant alleles characterised by *aroP579*, *mtr-24* and *tnaA1*.

In separate experiments using an overproducing strain carrying the *trpS378* allele and a plasmid carrying *trpE476DCBA* encoding a feedback-resistant anthranilate synthase, we have demonstrated that the temperature-sensitive allele *trpS378* may be used effectively at selected temperatures to favour either stability or productivity. We have found that such production strains carrying *trpS378* are more stable at about 30°C as compared to about 37°C. At about 37°C, productivity increases and stability decreases. Results are shown in Figure 2 for the production strain, JP6015/pMU91. The level of stability, in this case provided by *serA*+/- complementation, can be significantly enhanced by choice of incubation temperature. Similar results are obtained for other strains.

We have also established that the addition of yeast extract further decreases productivity at 30°C, such that the tryptophan level does not exceed 0.2 to 0.3g/L. This results in a significant increase in stability as shown in Figure 3. Some strains remain stable for more than 60 generations.

Feedback Inhibition of Anthranilate Synthase

Anthranilate synthase activity in wild-type strains of *Escherichia coli* is extremely sensitive to feedback-inhibition by tryptophan, showing about 50% inhibition at concentrations of tryptophan as low as 0.02mM. Feedback-resistant mutants have been reported in various publications, for example, Aiba *et al.*, CA 1 182 409, Tribe and Pittard. (1979). **Applied and Environmental Microbiol.** 38: 181-190, Aiba *et al.* (1982). **Applied and Environmental Microbiol.** 43: 289-297. In each case, isolation of such mutants involved selection for resistance to growth inhibition by tryptophan analogues.

Typically, mutants chosen for the purposes of tryptophan overproduction retained some feedback-inhibition, but the 50% figure occurred at a concentration of around 13mM rather than 0.02mM (see Aiba *et al.* CA 1 182 409). Where mutants conferring higher feedback-resistance were described (50% inhibition values greater than 20mM), they resulted in decreased accumulation of tryptophan, possibly because of impaired activity of the feedback-resistant enzymes (Aiba *et al.* (1982). **Applied and Environmental Microbiol.** 43: 289-297).

Two feedback-resistant mutants isolated by us were typical of those used previously in tryptophan overproduction, containing the alleles *trpE476* and *trpE382* encoding enzymes showing less than 10% inhibition of activity at 1mM tryptophan (see Example 2).

When a production strain with such mutations was used in a fermenter we observed that by the end of the fermentation, for every gram of tryptophan that had accumulated there was also approximately 20-60mg of each tyrosine and phenylalanine. Although these amino acids are a small fraction of the aromatic output they are side products which create major difficulties in the downstream recovery of tryptophan.

When we sought the basis for this accumulation we discovered that at tryptophan concentrations of 12g/L (60mM) these two feedback-resistant anthranilate synthases were inhibited by 60-80%. In other words, enzymes which appeared resistant at concentrations of 1mM were unable to function effectively under the actual conditions of an industrial fermentation. No state of the art makes reference to over-producing strains with enzymes resistant to feedback-inhibition at the very high levels likely to be present in a fermentation vat, whilst maintaining normal activity, thereby improving productivity.

In order to overcome this problem of inhibition of anthranilate synthase at high tryptophan concentrations we isolated a new feedback-resistant mutant (*trpE483*) which makes an anthranilate synthase enzyme which shows less than 10% inhibition of activity at concentrations of tryptophan as high as 13.5g/L (see Figure 4). When production strains with the *trpE483* allele were constructed and used in a fermentation under conditions which had previously produced approximately 20-60 mg of each tyrosine and phenylalanine per gram of tryptophan, no tyrosine and phenylalanine was detected and the yield of tryptophan remained high. This is in marked contrast to the earlier results

reported by Aiba *et al.* (**Applied and Environmental Microbiol.** (1982) **43**: 289-297) with anthranilate synthase mutants showing resistance to very high levels of tryptophan, where tryptophan productivity decreased.

The isolation of the *trpE483* allele was accomplished as described in Example 2, using a plasmid carrying the *trp* operon. Such a plasmid carrying the *trp* operon may readily be constructed using the known techniques such as restriction enzyme digestion, ligation and transformation (Maniatis, T., E.F. Fritsch and J. Sambrook, **Molecular Cloning: A Laboratory Manual**, Cold Spring Harbor Laboratory. (1982)). The *trp* operon may be derived from chromosomal DNA of *E. coli* or from the specialised transducing phage, (Φ 80pt190h (Hershfield, V. *et al.* (1974). **Proc. Natl. Acad. Sci. USA.** 71:3455-3459), and may be inserted into any one of a number of suitable vectors including, but not limited to, those derived from pSC101 (Cohen, S.N. and A.C. Chang (1977). **J. Bacteriol.** **132**, 734-737), R388 (Datta, N. and R.W. Hedges (1971). **J. Gen. Microbiol.** **72**: 349) etc. The vector may carry, in addition, the *serA*⁺ gene cloned by similar techniques. The plasmid so constructed is then transferred into the *E. coli* K-12 host by transformation.

The invention further relates to a method for growing and fermenting said *E. coli* K-12 strains showing high productivity. When microorganisms are grown in batch culture to produce an amino acid, the actual production of the amino acid is only required during the small number of generations which occur in the final fermentation vessel. For a 100 000L fermenter, only 5 to 10 generations may be required in the final fermentation vessel, whereas 50 or more generations are required to provide the inoculum for that vessel.

The use of the procedures described, utilising specific genetic mutations in conjunction with specific growth conditions, ensure the necessary strain stability whilst allowing maximum tryptophan productivity during growth in the final fermentation vessel. High yields of tryptophan may be achieved, even without the use of an antibiotic in the final fermentation (Example 6). The use of JP4735/pMU3028 results in high productivity of tryptophan with no significant formation of tyrosine and phenylalanine.

Deposits

The following *E. coli* K-12 strains were deposited at the culture collection Deutsche Sammlung von Mikroorganismen und Zellkulturen (DSM) in Braunschweig (Germany) on **14 July 1995** under the Budapest Treaty:

JP7847 under accession number DSM10119

JP6006 under accession number DSM10118

JP6768/pMU3018 under accession number DSM10120

JP6768/pMU3025 under accession number DSM10121

JP4735/pMU3028 under accession number DSM10122

JP6015/pMU91 under accession number DSM10123.

Example 1

Isolation Of Temperature Sensitive Tryptophan Auxotrophs With Mutations In The *trpS* Gene.

A strain of *Escherichia coli* K-12, KA56 (*galE*⁻, *thi*⁻) (Russell, R.R.B. and A.J. Pittard. (1971). **J. Bacteriol.** **108**: 790-798) was treated with the mutagen N-methyl-N'-nitro-N-nitrosoguanidine by the method of Adelberg, Mandel and Chen (**Biochem Biophys Res Commun.** (1965). **18**: 788-795). After treatment with mutagen, cells were washed and resuspended in minimal medium supplemented with casamino acids and with glycerol as carbon source, to utilise an enrichment procedure developed in this laboratory (Russell, R.R.B. and A.J. Pittard. (1971). **J. Bacteriol.** **108**: 790-798). After several hours growth at 32°C, the culture was shifted to 42°C and one hour later galactose was added to give a final concentration of 2%. Cells which lack uridine diphosphate galactose-4-epimerase (ie. *galE*) but are able to synthesise the enzymes galactokinase and galactose-1-phosphate uridyl transferase in response to the addition of galactose, accumulate UDP galactose which is toxic to the cell and causes cell lysis (Fukasawa, T., and H. Nikaido. (1959). **Nature** (London). **184**: 1168-1169). Cells which are unable to synthesise new enzymes in glycerol galactose casamino acids medium at 42°C do not form this compound and are not killed. Amongst such survivors one can find temperature-sensitive auxotrophs with mutations in the *trpS* gene. (Casamino acids contains very low levels of tryptophan). After 5 hours at 42°C in the presence of galactose, cells are recovered, washed and either (1) added to nutrient broth at 32°C and cultured to mid-exponential phase or (2) spread onto nutrient agar plates to give about 200 colonies per plate and incubated for 48h at 32°C. The colonies on each nutrient agar plate are replicated to two plates of MM and MM supplemented with L-tryptophan at 10⁻³M (MM+*Trp*). (MM represents half-strength Medium 56 (Monod, Cohen-Bazire and Cohen. (1951) **Biochim. Biophys. Acta** **1**, 585) solidified using 1% Oxoid No. 1 Agar, and containing glucose and thiamine. One set of plates (MM and MM+*Trp*), are incubated at 32°C and the other at 42°C. Colonies which can grow on MM at 32°C but not at 42°C but grow on the MM+*Trp* medium at 42°C, are potential temperature-sensitive tryptophan auxotrophs. To identify, amongst these, mutants with alterations in the *trpS* gene, it is necessary to prepare P1 transducing phage on a number of clones and transduce *aroB*⁺ into an *aroB*⁻ mutant such as AB2826 (Pittard, J. and B.J. Wallace. (1966). **J. Bacteriol.** **91**: 1494-1508) selecting *Aro*⁺ transductants on MM at 32°C. These transductants are then tested for their ability to grow on MM and MM+*Trp* at 42°C. Where the original tryptophan auxotroph is mutated in the *trpS* gene about 50% of the *Aro*⁺ transductants require tryptophan for growth at 42°C. In an alternative method the nutrient broth grown culture prepared after the galactose killing is used to prepare a P1 lysate. Again this lysate is used with AB2826 to select *aroB*⁺ transductants on MM at 32°C. Such transductants are then screened for any clones which can only grow on MM at 42°C if tryptophan is added to the medium. Figure 5 shows the growth curves of two

transductants, one being *aroB*⁺ *trpS378* (JP1451) and the other being *aroB*⁺ *trpS*⁺ (JP8820), in glucose minimal medium supplemented with various levels of tryptophan at 42°C. It can be seen that the temperature-sensitive phenotype can be reversed by high levels of tryptophan at the non-permissive temperature.

5

Example 2

Selection of a Mutant of Anthranilate Synthase Resistant to Feedback-inhibition by Very High Levels of Tryptophan

Plasmid pMU3018 (Figure 6) carries the *trp* promoter, the *trpE* gene and part of the *trpD* gene on a 2.9kb *Sma*I *Hind*III fragment. pMU3018 is derived from pMU578, which is a single-copy *TpR* plasmid carrying a *galK*'-*lac*'ZA fusion, similar to the promoter cloning vector pMU575 (Andrews, A.E., B. Lawley, and A.J. Pittard. (1991). **J. Bacteriol.** 173: 5068-5078), but with a *Sma*I *Eco*RI *Bgl*II linker replacing the *Sma*I site, and the *Dra*I fragments removed, deleting *lacY* and *lacA*. If pMU3018 DNA is digested with these two enzymes and the fragments electrophoresed in a low melting point agarose gel it is a simple matter to separate and purify the *trpEtrpD*' 2.9kb fragment and the larger 13kb vector fragment. This 2.9kb fragment was mutagenised with 50mM nitrous acid for 60 minutes following the method of Ray *et al.* (Ray, J.M., C. Yanofsky and R. Bauerle. (1988). **J. Bacteriol.** 170: 5500-5506), except that spermine (1mM) was added to the mutagenesis mixture. After mutagenesis, the fragment was religated with the larger 13kb fragment and the products of ligation were transformed into strain JP6768, an *E. coli* strain which is *trpR*⁻, and in which the *trpE* gene has been deleted from the chromosome but *trpDCB* and *A* are fully functional (*ΔtrpLE1413* (Miozzari, G.F. and C. Yanofsky. (1978). **J. Bacteriol.** 133: 1457-1466). Approximately 2000 transformants were selected on Luria agar containing trimethoprim. These were screened for growth on minimal medium supplemented with the tryptophan analogue 5-fluorotryptophan at 15mM. Clones which grew were potential feedback-resistant mutants altered in the enzyme anthranilate synthase. The anthranilate synthase activity of each of these clones was assayed in the presence of very high levels of tryptophan (13.5g/L) using the assay described in Cho, K.-O. and C. Yanofsky. (1988). **J. Mol. Biol.** 204: 41-50. A clone whose anthranilate synthase activity showed less than 10% inhibition at these very high levels of tryptophan was identified amongst the resistant mutants. The mutant allele present in this strain was called *trpE483*. In comparison, the allele *trpE476* encodes an anthranilate synthase with good resistance at 1g/L tryptophan but more than 60% inhibition at 13.5g/L tryptophan. Figure 4 compares the feedback sensitivity of anthranilate synthase from a strain with the wild-type allele (JP6768/pMU3018) and strains with the *trpE483* allele (JP6768/pMU3025) and with the *trpE476* allele (JP6768/pMU3019).

In order to reconstitute a *trp* operon with the *trpE483* allele, the 2.9kb fragment carrying it was joined to a 21kb *Hind*III *Sma*I fragment from the pMU575 derivative,

pMU1881, that carried the *trpDCBA* genes. This resulted in the plasmid pMU3027. This is summarised in Figure 7. This new *trp* operon incorporating *trpE483* was subsequently transferred into the pSC101-derivative pLG339 (Stoker, N.G. *et al* (1982), **Gene** **18**, 335-341), carrying *serA*⁺, to create pMU3028, which is shown in Figure 8.

- 5 Under conditions in which strains with the *trpE476* allele accumulated tyrosine and phenylalanine the strain with the *trpE483* allele produced no detectable tyrosine at all (see Example 6). It is obvious for a person skilled in the art that a broth without side products such as tyrosine and phenylalanine is preferably used for further purification -procedures.

Example 3

- 10 **Construction of a Strain of *E. coli* with a Temperature Sensitive *trpS* Allele and Mutations Preventing Normal Active Transport of Tryptophan into the Cell.**

The genes specifying the various systems for actively transporting tryptophan into *E. coli* have been identified, cloned and sequenced (Sarsero, J.P., P.J. Wookey, P. Gollnick, C. Yanofsky and A.J. Pittard. (1991). **J. Bacteriol.** **173**: 3231-3234; and
15 Honore, N. and S.T. Cole. (1990). **Nucleic Acids Research** **18**: 653). Mutants defective in each one of these systems (*TnaB*, *Mtr* and *AroP*) have also been described. The expression of the *TnaB* protein is prevented by a mutation in the *tnaA* gene (*tnaA1*), which has a polar effect on *tnaB* expression (Stewart, V. and C. Yanofsky. (1985). **J. Bacteriol.** **164**: 731-740). This is a particularly useful mutation because the *tnaA* gene
20 which is also inactivated, encodes the enzyme tryptophanase which could degrade tryptophan. Various mutations of the *mtr* gene have been described and mutants have been selected on the basis of resistance to the tryptophan analogue 5-methyl-tryptophan. One such mutation *mtr-24* was originally described by Hiraga (Hiraga, S., K. Ito, T. Matsuyama, H. Ozeki and T. Yura. (1968). **J. Bacteriol.** **96**: 1880-1881).

- 25 Mutants in the general aromatic transport system can also be isolated by selecting for resistance to analogues of the aromatic amino acids. The mutation *aroP579* was described by Brown (Brown K.D. (1970). **J. Bacteriol.** **104**: 177-188).

A strain which has a mutation in the *trpS* gene and mutations in each of the genes for the tryptophan transport systems can be constructed readily using the transposon Tn10
30 and Phage P1-mediated transduction. A prototrophic strain, W3110, was infected with the λ Tn10 transposon λ NK370 and tetracycline resistant colonies were selected as described by Kleckner, N., D.P. Barker, D.G. Ross and D. Botstein. (1978). **Genetics** **90**: 427450. By the use of P1 transduction, isolates were obtained in which Tn10 was closely linked to *aroP519*, *mtr-24* and *tnaA1*. P1 lysates could then be used to introduce
35 each of these mutations sequentially into the *trpS* strain in conjunction with selection of tetracycline sensitive derivatives according to the method of Bochner, B.R., H.C. Huang, G.L. Shieven and B.N. Ames. (1980). **J. Bacteriol.** **143**: 926-1033.

TrpS⁺ derivatives of such mutants could be obtained by transduction with a lysate from a *trpS*⁺ clone selecting for growth on plates containing 0.5mM tryptophan at 42°C.

Example 4

Comparison of Growth Rates of *trpS378* AND *trpS*⁺ Strains Defective in Active Transport of Tryptophan and in its Biosynthesis.

Tryptophan auxotrophs that possess the wild-type *trpS* allele and are able to actively transport tryptophan into the cell grow at a fast rate in minimal medium supplemented with tryptophan at levels as low as 5×10^{-5} M.

Tryptophan auxotrophs defective in the active transport of tryptophan require higher levels ($\sim 10^{-3}$ M) for optimal growth, whereas strains which additionally have the mutation *trpS378* require concentrations as high as 5×10^{-3} M before maximum growth rate is achieved.

Figure 1 compares the growth response to tryptophan of *trpS378* and *trpS*⁺ derivatives of a tryptophan auxotroph (*ΔtrpLE1413*) which also possesses mutations inactivating *Mtr*, *AroP* and *TnaB* proteins. JP6006 is derived from JP4153 by introduction of *ΔtrpLE1413* by P1 transduction using *Tn10* as a linked marker and isolation of a tetracycline-sensitive derivative, followed by introduction of *sac*⁺ by P1 transduction, using a P1 lysate grown on *sac*⁺ strain GA122 (Alaeddinoglu, N.G. and H.P. Charles. (1979). *J. Gen. Microbiol.* 110: 47-59). JP4153 is *aroF363 aroG103(FBR) aroH371(FBR) trpE382(FBR) trpR363 tyrR366 trpS378 aroP579 mtr-24 tna-1*. JP7847 is a *trpS*⁺ derivative of JP6006, isolated by P1 transduction.

Cells were grown in minimal medium supplemented with different levels of tryptophan at 30°C. Growth was measured by optical density with a Klett colorimeter and doubling times were calculated from the exponential phase of each growth curve.

Example 5

The Effect of Temperature and Yeast Extract Addition on Strain Stability and Productivity.

Strain stability may be tested by measurement of the productivity of tryptophan and anthranilate of cultures in shake flasks, where 1% serial transfers are made every 24h. Biomass is limited to approximately 0.4mg/mL by phosphate concentration, by the phosphate available in yeast extract, or by a mixture of the two. Passage through each flask in the series represents a 100-fold increase in cell number, or 6.7 generations.

Tryptophan productivity characteristically remains close to 100% of the normal value for the strain, with negligible anthranilate detected, for a number of flasks. In a flask some distance down the series, tryptophan productivity generally falls suddenly to 40%-50%, with the concomitant appearance of anthranilate. Cell counts have indicated that the transition from high tryptophan productivity with no anthranilate to low tryptophan productivity with anthranilate corresponds to an increase in segregants or mutants from 0-10% to 40-70%.

The medium for each strain is prepared from sterile stock solutions as follows:

glucose (20%) or sucrose (20%)	10mL
MOPS Minimal Medium (x10)*	20mL

B1 (thiamine) (0.01%)	0.2mL
phosphate (15mM KH_2PO_4)	2.0mL
tetracycline (10mg/mL), if required	0.2mL
sterile distilled water	170mL

- 5 *MOPS Minimal Medium (x10) contains per litre: 167.44g MOPS, 1.41g $\text{Na}_3\text{citrate} \cdot 2\text{H}_2\text{O}$, 0.13g $\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$, 19.2g NH_4Cl , 4.0g $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$, 2.4g KCl , 0.15mg $\text{CaCl}_2 \cdot 2\text{H}_2\text{O}$ and trace elements (14 μg $\text{CoCl}_2 \cdot 6\text{H}_2\text{O}$, 5 μg $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$, 48 μg H_3BO_3 , 57 μg $\text{ZnSO}_4 \cdot 7\text{H}_2\text{O}$, 32 μg $\text{MnCl}_2 \cdot 4\text{H}_2\text{O}$ and 8 μg $(\text{NH}_4)_6\text{Mo}_7\text{O}_{24} \cdot 4\text{H}_2\text{O}$)

A 10mL culture is inoculated from a fresh patch of the test strain, and incubated
10 overnight with shaking at 30°C. The procedure from transformation until this stage represents about 34 generations, which are not included in the calculations. The overnight culture is used to inoculate the first flask in the series.

1% transfers (100 μL into 10mL) are made at 24h intervals until the culture's productivity of tryptophan falls, with the simultaneous appearance of anthranilic acid.
15 Under the conditions of these experiments each culture reached stationary phase before being transferred and each flask represents approximately 6.7 generations. Where the dramatic changes in tryptophan and anthranilic acid levels occurred in the sixth flask for example, stability would be recorded as 5x6.7 or 33.5 generations. At the time of each transfer the optical density of the 24h culture is measured, a sample is centrifuged and the
20 supernatant is filtered through a disposable filter (Millipore, 0.45 μm) using a syringe. The concentration of tryptophan and anthranilic acid are determined by HPLC.

Measurement of productivity (Y p/x) in flasks

The test strain is grown at the required temperature with shaking, and productivity is measured after 24h and 48h. The medium is the same as that used in stability trials. A
25 10mL culture is inoculated from a fresh patch, and incubated overnight with shaking. This is used to inoculate the test flask, containing 15mL of the same medium. After 24h a sample is removed. Optical density is measured at 660 λ using a Spectrophotometer and dry weight is calculated using a standard curve. The sample is centrifuged, filtered, and tryptophan, tyrosine and anthranilic acid concentrations are measured by HPLC using
30 appropriate standards. The productivity (Y p/x) is defined as yield of tryptophan (g/L) divided by yield of biomass or dry weight (g/L).

The effect of temperature of incubation on both stability and productivity for an overproducing strain carrying the *trpS378* allele and a plasmid carrying the *trp* operon encoding a feedback-resistant anthranilate synthase, is shown in Figure 2.

35 Low temperatures favour high stability and low productivity, whilst higher temperatures favour productivity at the expense of stability. This may be demonstrated in various production strains, with different primary selections. The data in Figure 2 is for JP6015/pMU91 and the primary selection is for *Ser*⁺. JP6015 is derived from JP4153 (see Example 4) by introduction of *sac*⁺ by transduction, and introduction of *serA*⁻ by
40 cotransduction with a closely linked *Tn10* transposon, and subsequent selection of a

tetracycline sensitive derivative. pMU91 is a plasmid derived from pSC101 (Cohen, S.N. and A.C. Chang (1977). *J. Bacteriol.* **132**: 734-737), carrying Tc^R , *trpE476DCBA* and *serA*⁺ (see Figure 9). The *trpE476DCBA* allele was isolated using the specialised transducing phage $\Phi 80pt190h$ (Herschfield, V. *et al* (1974). *Proc. Natl. Acad. Sci. USA* **71**: 3455-3459). A *trpE*⁻ strain carrying $\Phi 80pt190h$ was plated on minimal medium containing 1mM 5-methyltryptophan (5MT). A pool of cells was induced by ultraviolet light to produce a lysate which was used in a subsequent transduction, selecting *Trp*⁺5MTR transductants. Several of these were assayed for anthranilate synthase activity, and the *trpE476DCBA* allele was characterised as encoding an anthranilate synthase with 70% of full activity at 10mM L-tryptophan. The *trp* genes were cloned on a 7.9kb *XhoI/SalI* fragment into the *XhoI* site of pSC101. The *serA*⁺ gene was introduced into the *XhoI* site on a 2.9kb *SalI* fragment.

The effect of the presence or absence of yeast extract on both stability and productivity can also be demonstrated in various tryptophan over-producing strains.

The data in Figure 3, using JP6015/pMU91 and a *Ser*⁺ primary selection, demonstrates the use of yeast extract to decrease productivity and increase stability.

Example 6

Tryptophan Production with *Escherichia coli* JP6015/pMU91

Single colonies of *Escherichia coli* K-12 strain JP6015/pMU91 were produced on MM agar (see example 1) supplemented with glucose (2g/L), yeast extract (5g/L) and tetracycline (5mg/L) by incubation at 30°C for 48 h. One single colony was further propagated in a 10mL culture (100mL flask) by incubation for approximately 16h at 30°C and at 250rpm (revolution per minute).

The medium for the culture was prepared from sterile stock solutions as follows:

glucose (20%)	10mL
MOPS minimal medium (x10)	20mL (see Example 5)
yeast extract (20%)	1mL
tetracycline (10 mg/l)	0.1mL
sterile distilled water	170mL

One mL of this culture of *Escherichia coli* K-12 strain JP6015/pMU91 was inoculated into 300mL of a seed medium (composition shown in Table 1) charged in an Erlenmeyer's flask of 2000mL volume, and cultured with shaking at 30°C for 24h on a rotary shaker at 150rpm.

Table 1

Composition of Seed Medium	
glucose.H ₂ O	4g/L
yeast extract	1.1g/L
morpholino-propane sulfonic acid	16.7g/L
tri sodium citrate.2H ₂ O	0.14g/L
FeSO ₄ .7H ₂ O	13mg/L

Composition of Seed Medium	
MgSO ₄ .7H ₂ O	0.4g/L
(NH ₄) ₂ SO ₄	1.29g/L
KCl	0.24g/L
KH ₂ PO ₄	1.05g/L
thiamine hydrochloride	5mg/L
tetracycline	2.5mg/L
trace elements	2mL/
pH adjustment to approx. 7.0 with 25% aqueous NH ₄ OH	
The trace elements are comprising:	
Na ₂ MoO ₄ .H ₂ O	0.15g/L
H ₃ BO ₃	2.5g/L
CoCl ₂ .6H ₂ O	0.7g/L
CuSO ₄ .5H ₂ O	0.25g/L
MnCl ₂ .4H ₂ O	1.6g/L
ZnSO ₄ .7H ₂ O	0.3g/L

70mL of the resulting seed culture was inoculated into 700mL of a pre fermentation medium (composition shown in Table 2) charged in a 2L jar fermenter, and culturing was carried out at 30°C for 24h. The pH value of 6.7 was controlled by 25% aqueous ammonia; pO₂ was kept above 40% by aeration with a rate of $\frac{1}{3}$ vvm and stirring with a speed between 280 and 380rpm.

Table 2

Composition of Pre Fermentation Medium	
glucose.H ₂ O	27.5g/L
yeast extract	7.5g/L
tri sodium citrate.2H ₂ O	1g/L
FeSO ₄ .7H ₂ O	1.1g/L
MgSO ₄ .7H ₂ O	3.15g/L
(NH ₄) ₂ SO ₄	8.65g/L
KH ₂ PO ₄	0.75g/L
thiamine hydrochloride	24mg/L
tetracycline	2.5mg/L
K ₂ SO ₄	2.3g/L
trace elements (see table 1)	2mL/L

The resulting preculture having an OD value of 20 (measured at 660nm) was inoculated into 6.3L of the main fermentation medium with the composition shown in Table 3, charged in a 10L fermenter.

Table 3

Composition of Main Fermentation Medium	
glucose.H ₂ O	27.5g/L
tri sodium citrate.2H ₂ O	1g/L
FeSO ₄ .7H ₂ O	1.4g/L
MgSO ₄ .7H ₂ O	3.15g/L

Composition of Main Fermentation Medium	
(NH ₄) ₂ SO ₄	8.65g/L
KH ₂ PO ₄	1.5g/L
K ₂ SO ₄	2.3g/L
trace elements (see table 1)	4mL/L

The fermentation was carried out at 33°C with aeration at 0.5vvm and keeping PO₂ above 40% by stirring the culture between 700 and 1200rpm; pH was maintained at 7.0 using 25% aqueous ammonia. After 6.5h a solution of 620g/L(w/v) glucose was continuously added to the culture in such a manner that the concentration of glucose in the fermenter did not exceed the value of 17g/L. After 32h the fermentation was completed. The amount of L-tryptophan and of the side products L-phenylalanine and L-tyrosine accumulated was quantitatively determined by high performance liquid chromatography. The results are reported in Table 4.

Table 4

Strain	L-Tryptophan (g/L)	L-Phenylalanine (g/L)	L-Tyrosine (g/L)
JP6015/pMU91	18.3	1.0	0.8
JP4735/pMU3028	19.5	0	0

Example 7

Tryptophan Production with *Escherichia coli* JP4735/pMU3028

Single colonies of *Escherichia coli* K-12 strain JP4735/pMU3028 were produced on MM agar (see example 1) supplemented with glucose (2g/L), yeast extract (5g/L) and tetracycline (2.5mg/L) by incubation at 30°C for 48h. One single colony was further propagated in a 10mL culture (100mL flask) by incubation for approximately 16h at 30°C and at 250rpm.

The medium of the culture was prepared from sterile stock solutions as follows.

glucose (20%)	10mL
MOPS minimal medium (x10)	20mL (see Example 5)
yeast extract (20%)	1mL
tetracycline (10 mg/l)	0.05mL
sterile distilled water	170mL

One mL of this culture of *Escherichia coli* K-12 strain JP4735/pMU3028 was inoculated into 300mL of a seed medium (composition shown in Table 1) charged in an Erlenmeyer's flask of 2000mL volume, and cultured with shaking at 30°C for 24h on a rotary shaker at 150rpm. 70mL of the resulting seed culture was inoculated into 700mL of a pre-fermentation medium (composition shown in Table 2) charged in a 2L jar fermenter, and culturing was carried out at 30°C for 24h. The pH value of 6.7 was controlled by 25% aqueous ammonia; pO₂ was kept above 40% by aeration with a rate of 1/3 vvm and stirring with a speed between 280 and 380rpm.

The resulting preculture having an OD value of 20 (measured at 660nm) was inoculated into 6.3L of the fermentation medium with the composition shown in Table 3, charged in a 10L fermenter.

The fermentation was carried out at 33°C with aeration at 0.5vvm and keeping pO₂ above 40% by stirring the culture between 700 and 1200rpm; pH was maintained at 7.0 using 25% aqueous ammonia. After 6.5 hours a solution of 620g/L(w/v) glucose was continuously added to the culture in such a manner that the concentration of glucose in the fermenter did not exceed the value of 27g/L. After 45h the fermentation was completed. The amount of L-tryptophan accumulated was quantitatively determined by high performance liquid chromatography. The results are reported in Table 4.

The claims defining the invention are as follows:

1. An *E. coli* strain having increased productivity for L-tryptophan, said strain comprising a genome having a mutant *trpS* gene encoding a defective tryptophanyl-tRNA synthetase, said synthetase being characterized by a temperature-dependent tryptophan auxotrophy and selected at 27°-30°C., and said strain having a further mutation in at least one gene selected from the group consisting of *mtr*, *aroP*, *tnaA* and *tnaB*, thereby rendering the strain defective in tryptophan transport.

2. The strain according to claim 1, wherein said further mutation is selected from *aroP579*, *mtr-24* or *tnaA1*.

3. The strain according to claim 1 or 2, wherein said mutant gene encoding defective tryptophanyl-tRNA synthetase is the *trpS378* allele, present in *E. coli* JP6006 deposited with DSM (Deutsche Sammlung für Mikroorganismen, Braunschweig, Germany) under accession number DSM10118.

4. The strain according to claim 1 or 2, said strain carrying a plasmid carrying the tryptophan operon encoding an anthranilate synthase enzyme freed from feedback inhibition by tryptophan.

5. The strain according to claim 4, wherein said plasmid is pMU3025 and carries the *trpE483* allele, said plasmid being characterized as shown in FIG. 6c and present in *E. coli* JP6768/pMU3025 deposited with DSM under the accession number DSM10121.

6. The strain according to claim 4, wherein said plasmid is pMU3028 and carries the *trpE483* allele and *serA*⁺, said plasmid being characterized as shown in FIG. 8 and present in *E. coli* JP4735/pMU3028, deposited with DSM under the accession number DSM10122.

7. The strain according to claim 4, wherein said plasmid is pMU91 and carries the *trpE476* DCBA genes and *serA*⁺, said plasmid being characterized as shown in FIG. 9 and obtainable from *E. coli* JP6015/pMU91, deposited with DSM under the accession number DSM 10123.

8. The strain according to claim 1 or 2, said strain having at least one mutation selected from the group consisting of *trpR*, *tyrR*, *serA*, *aroG*, *aroH*, and *trpE*.

9. An *E. coli* strain having increased productivity for L-tryptophan, substantially as herein described with reference to Example 3.



10. A method for stabilizing the characteristics of an *E. coli* strain having productivity for L-tryptophan during the growth of inoculum, said method comprising the steps of:

introducing into the genome of said *E. coli* strain a mutant gene encoding a partially defective tryptophanyl-tRNA synthetase, said synthetase being characterised by a temperature dependent tryptophan auxotrophy and selected at 27°-30°C.;

introducing at least one further mutation in the genes of *aroP*, *mtr*, *tnaA* or *tnaB*; and

cultivating said strain at 27°-30°C.

11. The method according to claim 10, wherein said mutation is selected from *aroP*579, *mtr*-24 or *tnaA*1.

12. The method according to claim 10 or 11, wherein said *E. coli* strain carries a plasmid.

13. The method according to claim 12, wherein said plasmid carries the *trpE*483 allele.

14. The method according to any one of claims 10 to 13, wherein yeast extract is added during inoculum growth.

15. A method for stabilizing the characteristics of an *E. coli* strain having productivity for L-tryptophan during the growth of inoculum, which method is substantially as herein described with reference to Example 3.

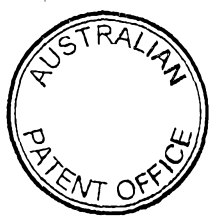
16. A method of producing L-tryptophan by fermentation which comprises:

cultivating an *E. coli* strain according to claim 1 or 2, in an appropriate culture medium at about 30°C., limiting growth by adjusting the concentration of available phosphate;

fermenting said medium at a temperature in the range of about 33°C. to 37°C., in the absence of yeast extract; and

recovering tryptophan accumulated in the culture medium.

17. The method according to claim 16, wherein said cultivation is carried out in the presence of yeast extract.



18. The method according to claim 16 or 17, wherein said fermentation is carried out in the absence of antibiotics.

19. A method of producing L-tryptophan by fermentation which comprises:

cultivating an *E. coli* strain according to claim 9, in an appropriate culture
5 medium at about 30°C., limiting growth by adjusting the concentration of available phosphate;

fermenting said medium at a temperature in the range of about 33°C. to 37°C., in the absence of yeast extract; and

recovering tryptophan accumulated in the culture medium.

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Dated 21 September, 1999

Degussa Aktiengesellschaft

Patent Attorneys for the Applicant/Nominated Person

SPRUSON & FERGUSON



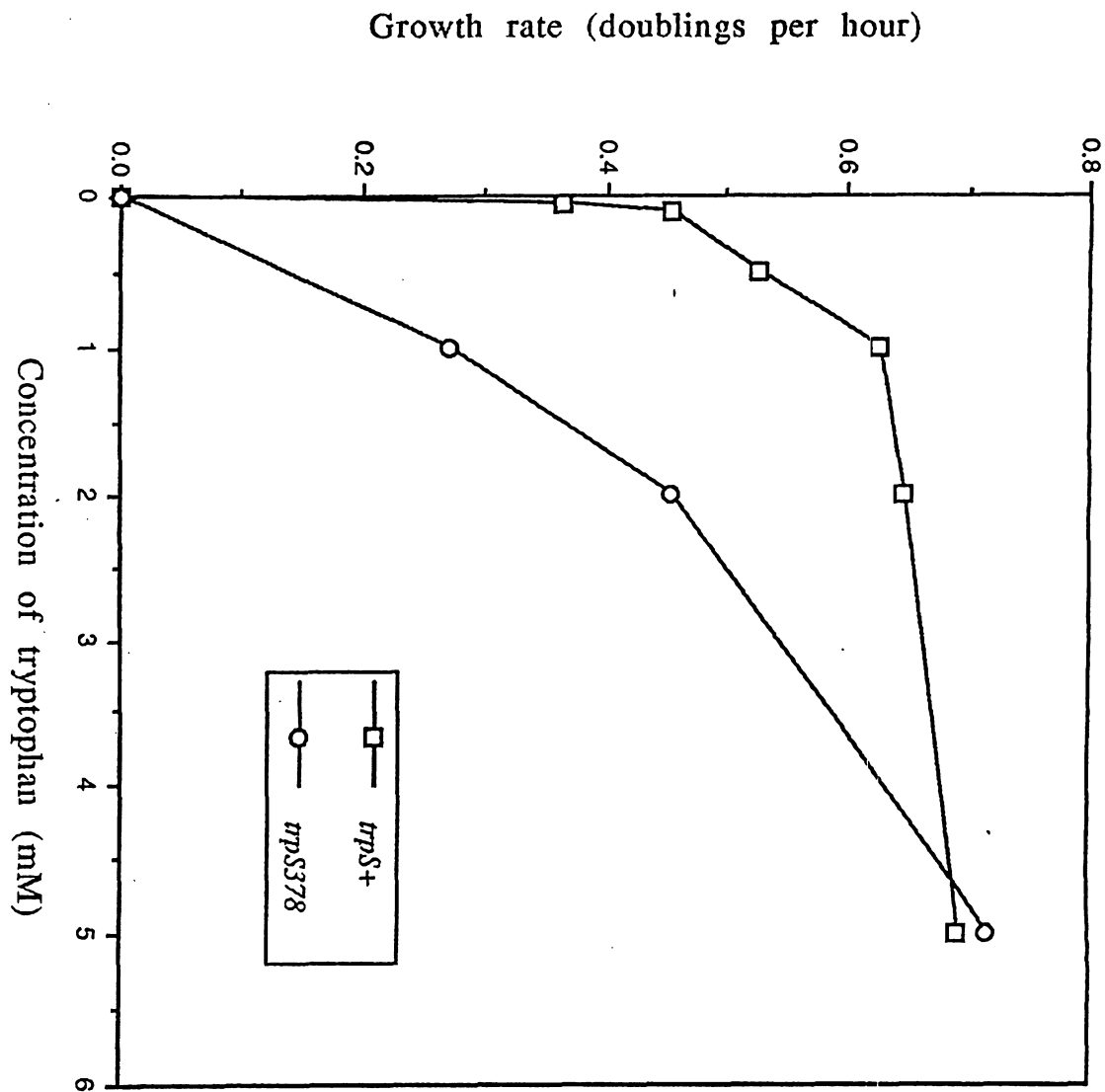


Fig. 1

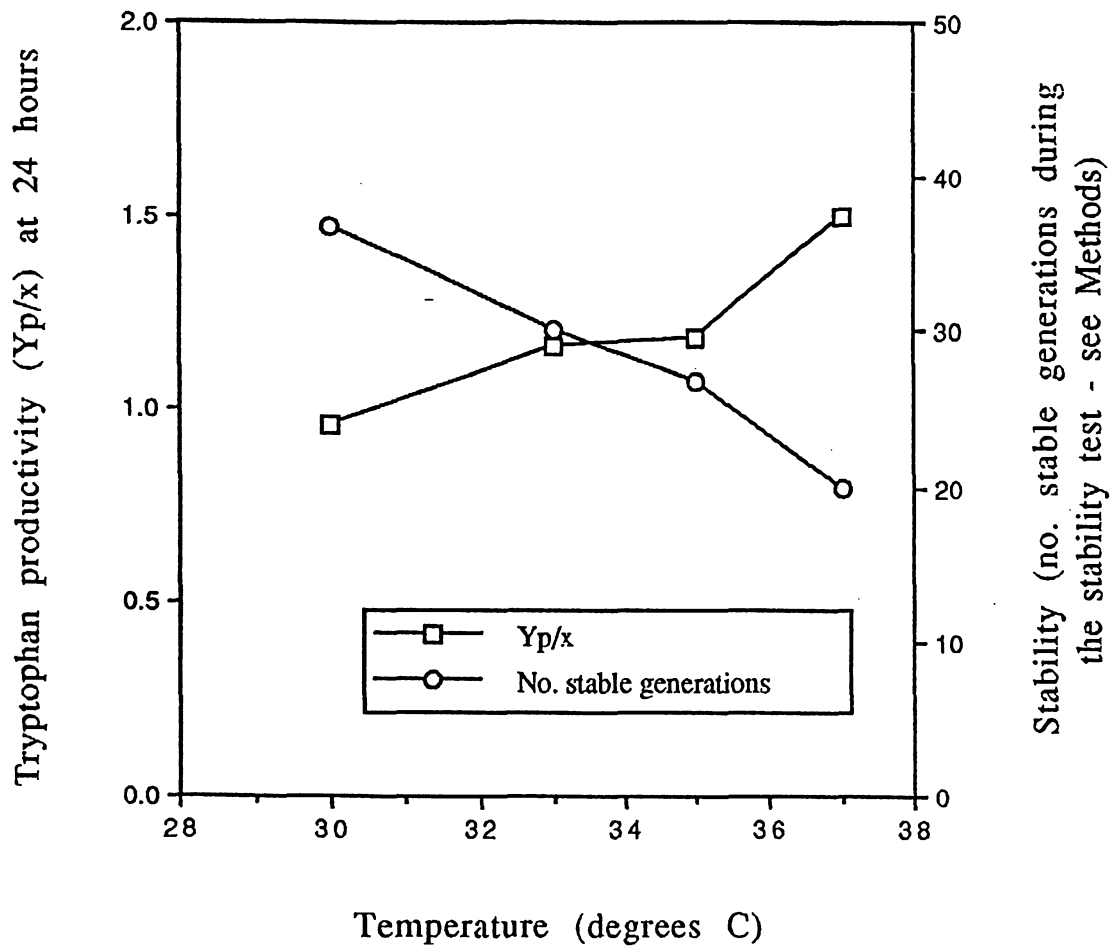


Fig. 2

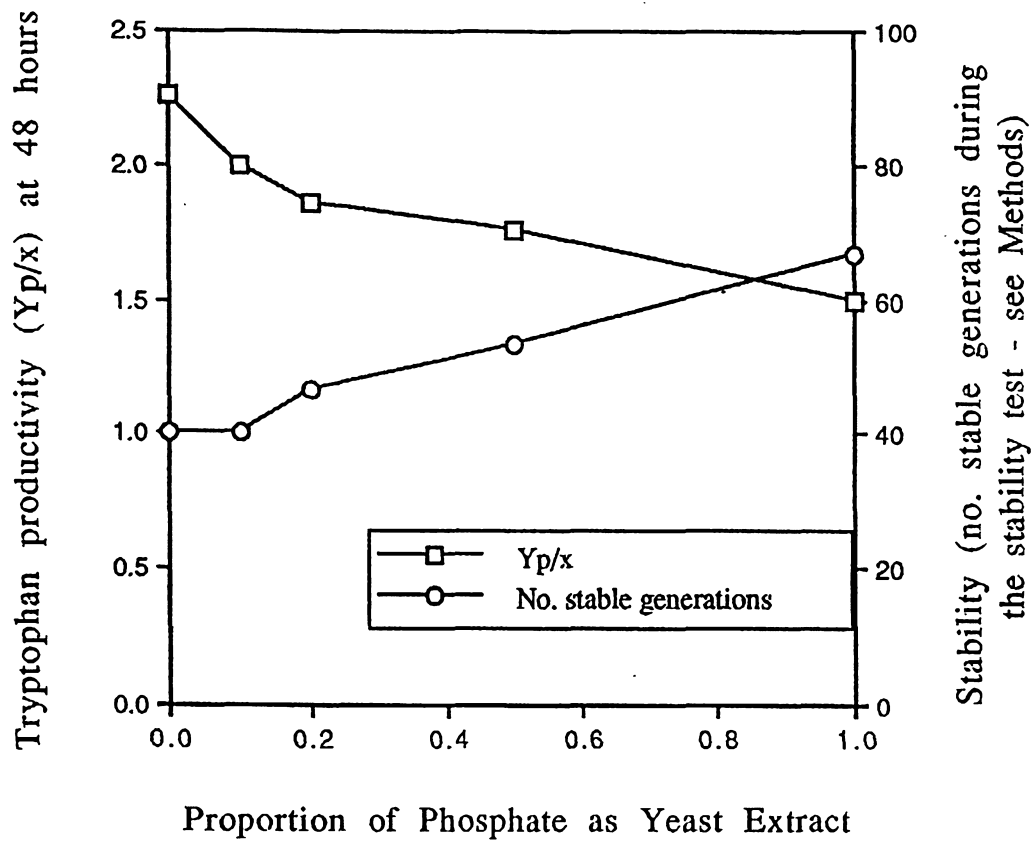


Fig. 3

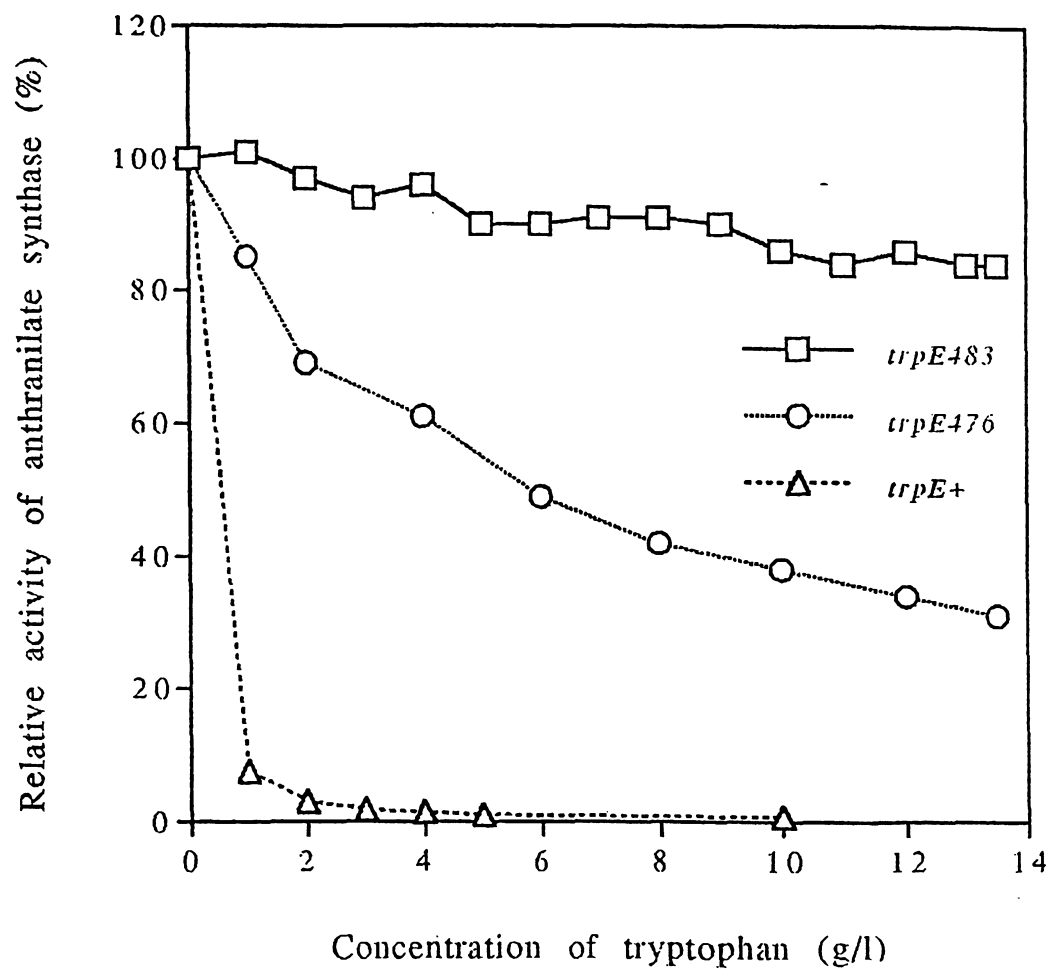


Fig. 4

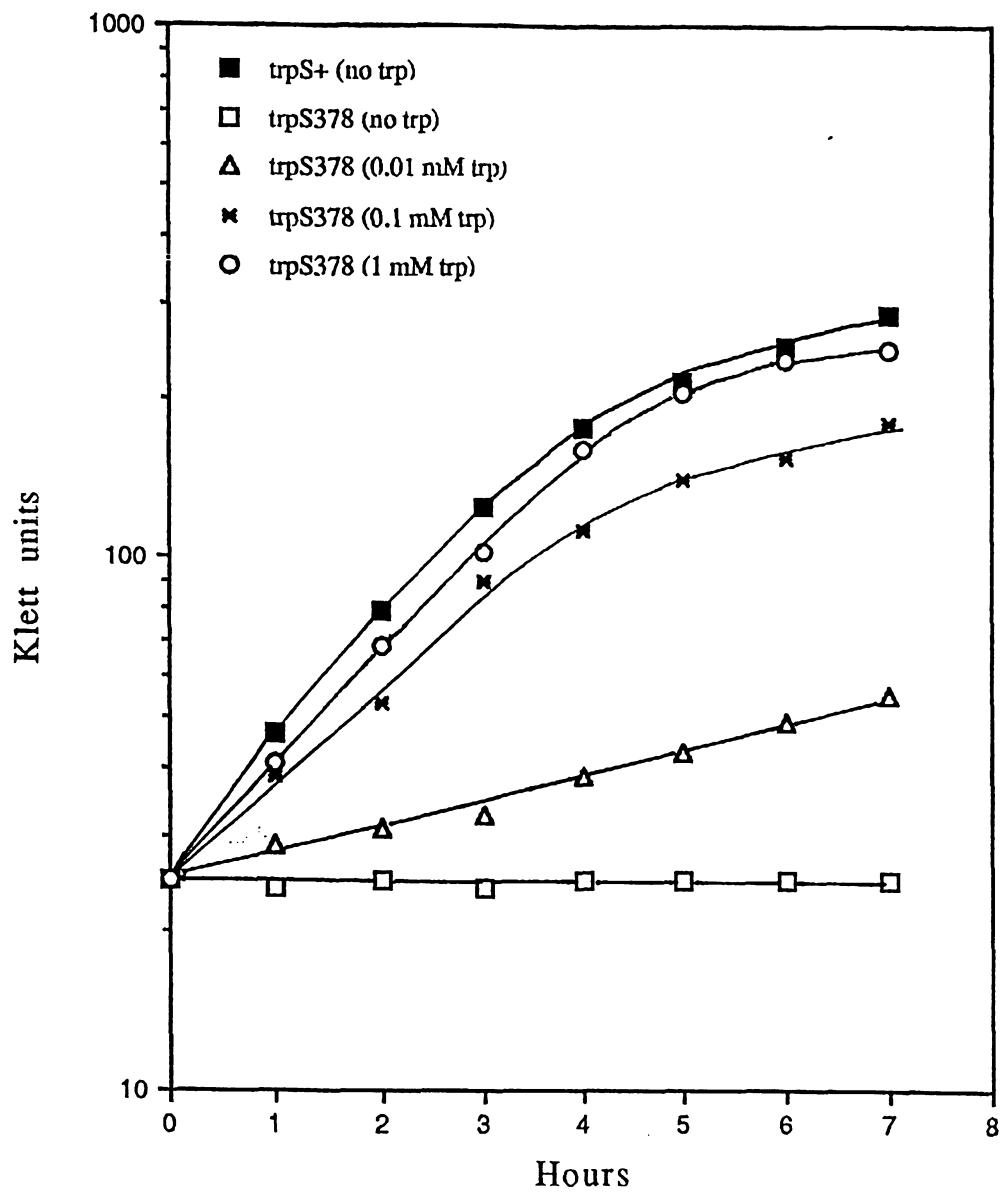


Fig. 5

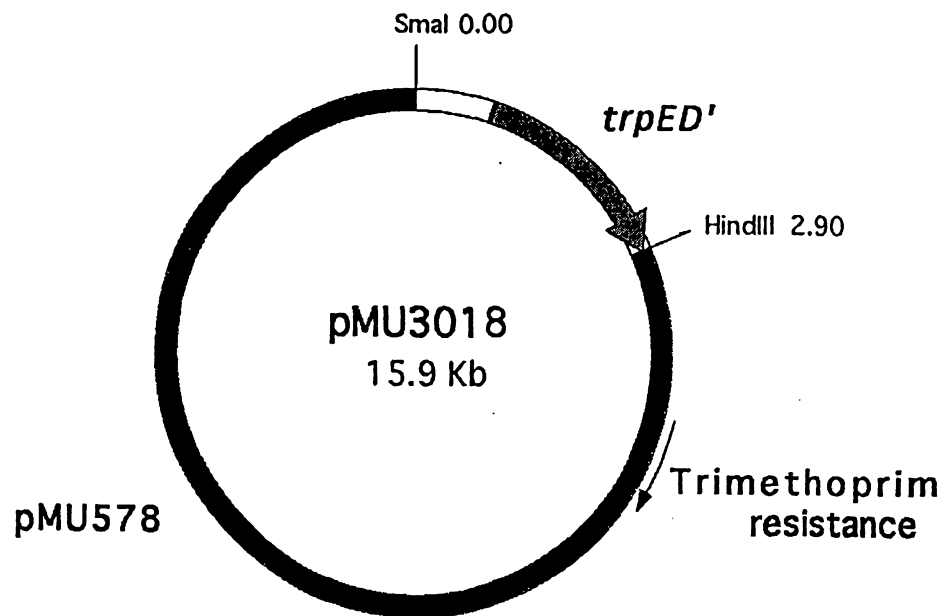


Fig. 6 a

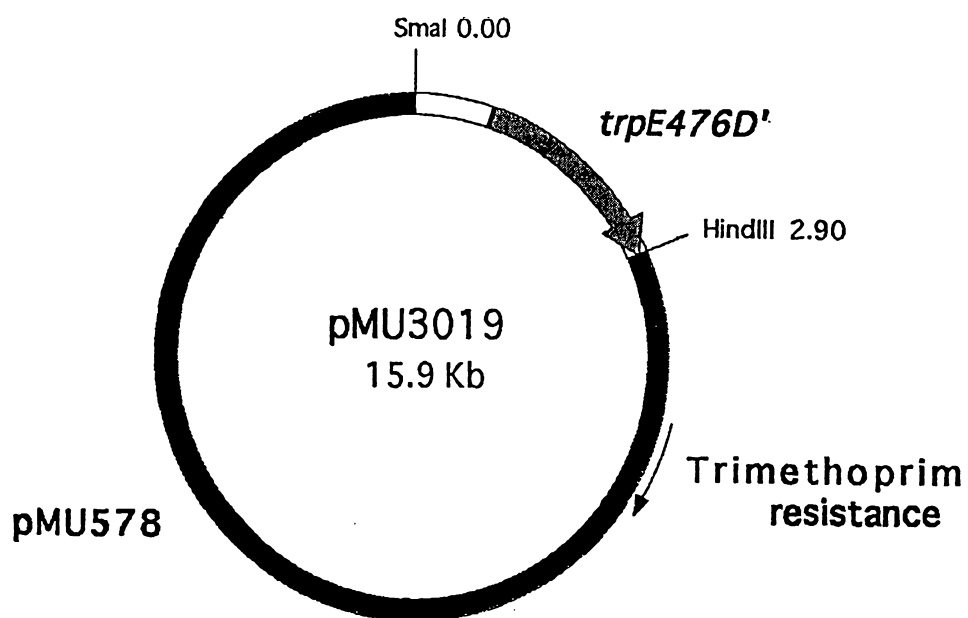


Fig. 6 b

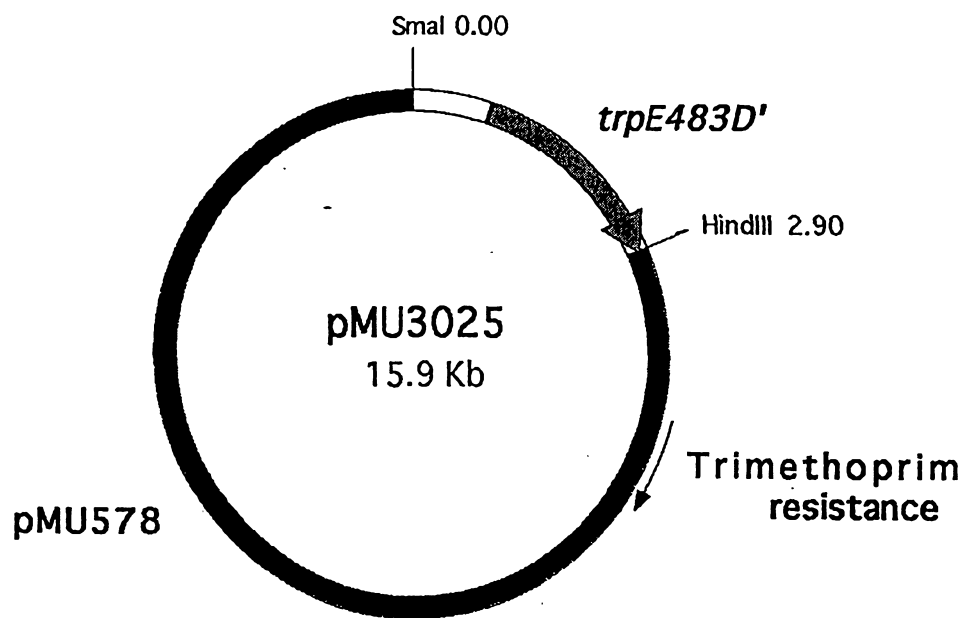


Fig. 6 c

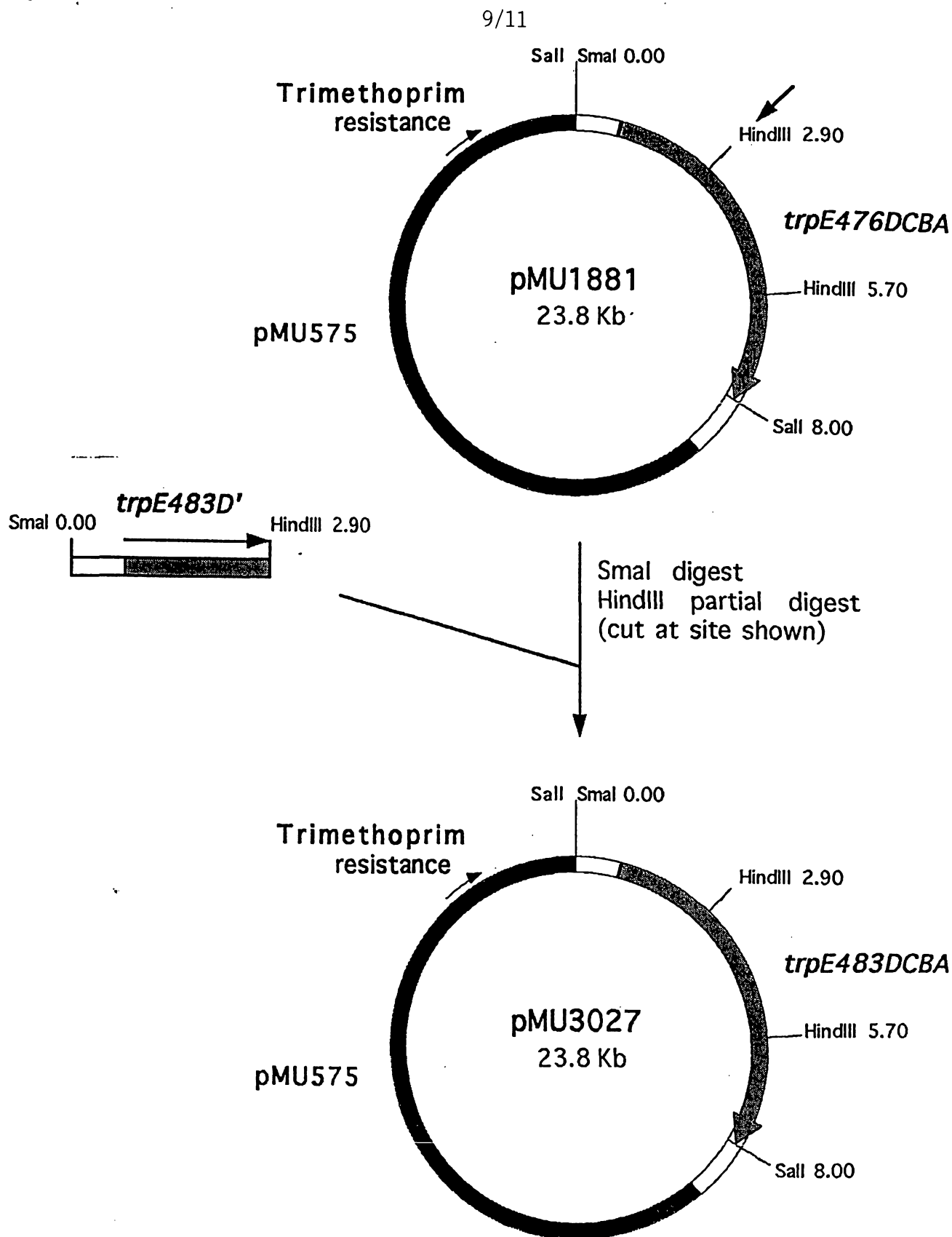


Fig. 7

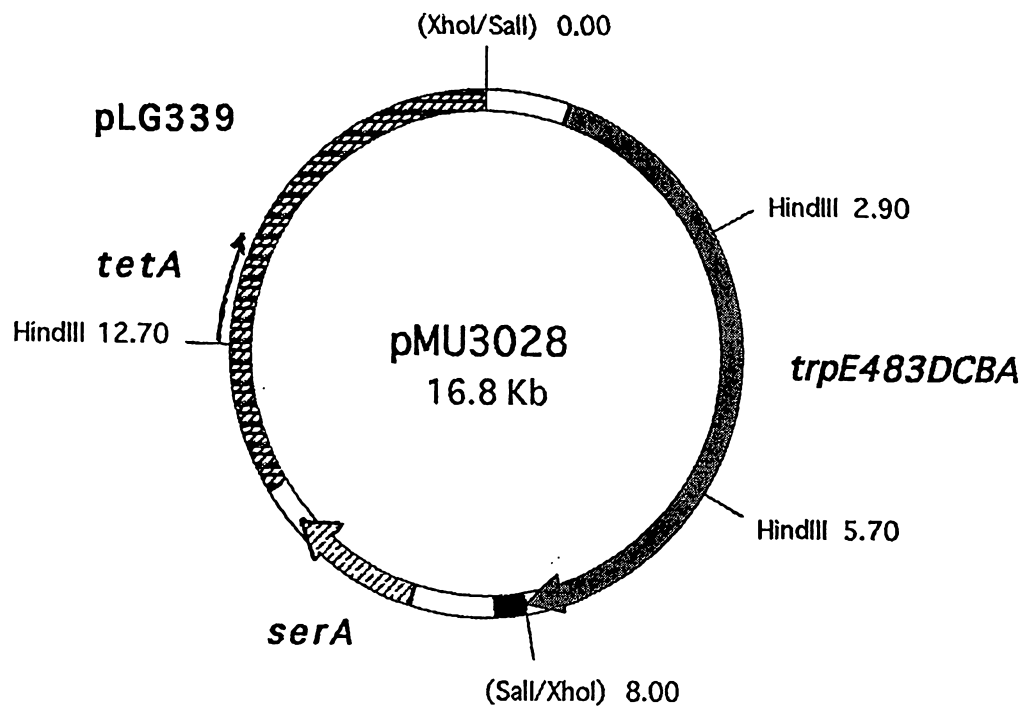


Fig. 8

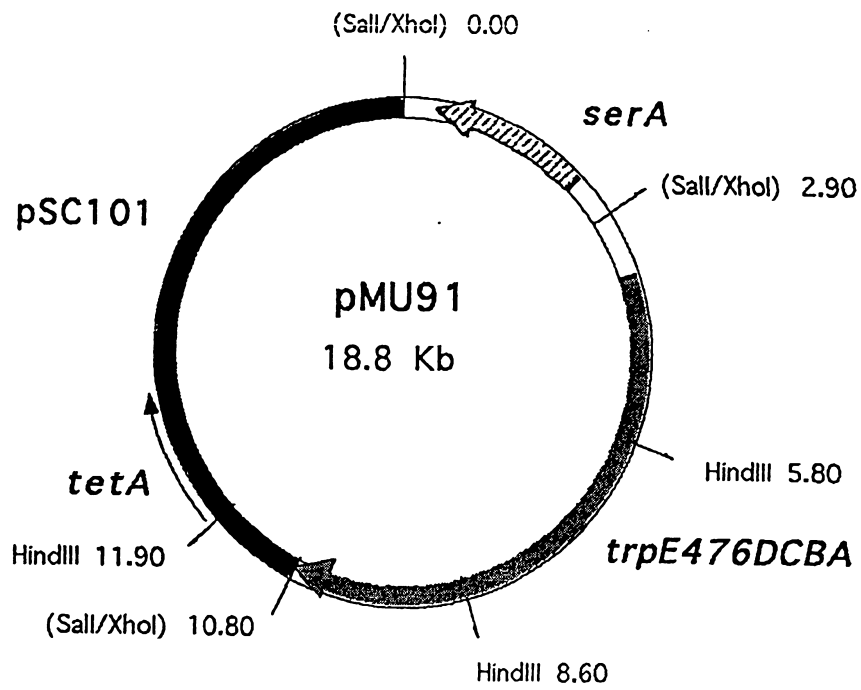


Fig. 9