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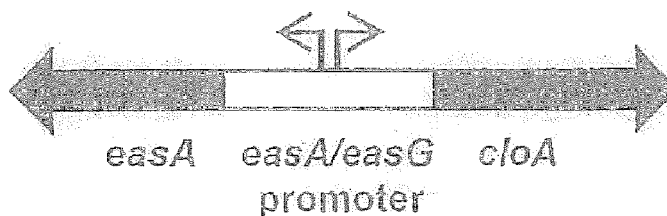


FIGURE 8

(57) Abstract: The present invention provides a method of producing lysergic acid and other ergot alkaloids by genetic modification of a fungus. A strain of fungus comprising *Aspergillus fumigatus* (*A. fumigatus*) and expressing one or more genes of the ergot alkaloid biosynthesis pathway from one or more fungus selected from the group consisting of *Epichloë festucae* var. *lolii* x *Epichloë typhina* isolate Lpl (E. sp. Lpl); *Claviceps* species; *Claviceps africana* (*C. africana*); *Claviceps gigantea* (*C. gigantea*); *Epichloë coenophiala* and *Periglandula* species, wherein gene *easA* or gene *easM* is inactivated in said *A. fumigatus*, is provided.



## PRODUCTION OF LYSERGIC ACID BY GENETIC MODIFICATION OF A FUNGUS

## CROSS-REFERENCE TO RELATED APPLICATION

This utility patent application claims the benefit of co-pending U.S. Provisional Patent Application Serial No. 62/012,658, filed on June 16, 2014. The entire contents of U.S. Provisional Patent Application Serial No. 62/012,658 is incorporated by reference into this utility patent application as if fully written herein.

## SEQUENCE LISTING

Following the Abstract of the Disclosure is set forth a paper copy of the SEQUENCE LISTING in written form (.PDF format) having SEQ ID NO:1 through SEQ ID NO:7. The paper copy of the SEQUENCE LISTING is incorporated by reference into this application. A SEQUENCE LISTING in computer-readable form (.txt file) having SEQ ID NO:1 through SEQ ID NO. 7 accompanies this application and is incorporated into this application. A Statement Of Identity Of Computer-Readable Form And Written Sequence Listing also accompanies this application.

## GOVERNMENT SUPPORT

This invention was made with government support under Grant No. 2012-67013-19384 and Grant No. 2008-35318-04549 awarded by USDA NIFA and Hatch funds. The government has certain rights in this invention.

## BACKGROUND OF THE INVENTION

## 1. Field of the Invention

The present invention relates to a method of producing lysergic acid by genetically modifying a fungus. A method for producing dihydroergot alkaloids (dihydrolysergic acid and dihydrolysergol) and lysergol are also provided. This invention discloses the heterologous expression of lysergic acid and novel ergot alkaloids in *Aspergillus fumigatus*.

## 2. Description of the Background Art

Ergot alkaloids derived from lysergic acid have impacted human health for millennia, initially as toxins and more recently as pharmaceuticals; however, important aspects of ergot alkaloid biosynthesis remain unsolved. Ergot alkaloids are pharmaceutically and agriculturally relevant secondary metabolites synthesized by several species of fungi. Historically, ergot alkaloids caused periodic mass human poisonings due to infection of grain crops by the ergot fungus *Claviceps purpurea* (Matossian, 1989). Agriculturally, ergot alkaloids in forage grasses colonized by endophytic *Epichloë* spp. [including many fungi recently realigned from genus *Neotyphodium* (Leuchtman et al., 2014)] continue to reduce weight gain and fitness in grazing animals (Schardl et al., 2012; Panaccione et al., 2014). Clinically, the structural similarities of ergot alkaloids to monoamine neurotransmitters allow them to treat cognitive and neurological maladies including dementia, migraines, and Parkinson's disease in addition to endocrine disorders such as type 2 diabetes and hyperprolactinemia (e.g., Baskys and Hau, 2007; Morren and Galvez-Jimenez, 2010; Perez-Lloret and Rascol, 2010; Winblad et al., 2008) (see ergot chart below). Indeed, the neurotransmitter-mimicking activities of ergot alkaloids are most infamously evident in the psychoactive drug LSD, a semisynthetic lysergic acid derivative (Hoffman, 1980). Several of the more important pharmaceutical ergot alkaloids are semi-synthetic dihydroergot alkaloids (dihydro prefix abbreviated as DH in subsequent text); natural DHergot alkaloids producers exist, but the genetic basis for their biosynthesis is unknown. In some embodiments of the invention, controlling the ergot alkaloid pathway will facilitate metabolic engineering strategies to produce libraries of ergot derivatives with potentially altered pharmacology. Moreover, by understanding different branches of the ergot alkaloid pathway, we will be able to prepare alternate starting materials for more efficient pharmaceutical synthesis.

Examples of pharmaceutical ergot alkaloids and their uses and derivations<sup>1</sup>

<b>Ergot Alkaloid (brand name)</b>	<b>Clinical use(s)</b>	<b>Current semisynthetic derivation</b>	<b>Efficient semisynthetic derivation</b>
Nicergoline (Sermion)	Senile dementia, Alzheimer's, cerebral thrombosis	From LA via other ergot alkaloids	From DHlysergol, lysergol, or DHLA
Cabergoline	Hyperprolactinemia,	From LA via other ergot	From DHLA

(Caberlin, Dostinex)	pituitary prolactinomas	alkaloids	
Pergolide (Permax)	Parkinson's (elsewhere, withdrawn in USA, 2007)	From LA via other ergot alkaloids	From DHlysergol, lysergol, or DHLA
Bromocriptine (Parlodel, Cycloset)	Type 2 diabetes, Parkinson's, hyperprolactinemia	From $\alpha$ -ergocryptine or LA via other ergot alkaloids	
Ergoloid mesylates (Hydergine)	Senile dementia	From ergopeptines or LA via other ergot alkaloids	From DHergopeptines or DHLA
DHergotamine (DHE 45, Migranal)	Migraines	From ergotamine or LA via other ergot alkaloids	From DHergotamine or DHLA

<sup>1</sup> Abbreviations: LA, lysergic acid; DH, dihydro (meaning lacking a double bond in fourth ring of ergoline nucleus)

Lysergic acid that is used for pharmaceutical production is presently synthesized in one of two methods known by those skilled in the art generally. The first known method involves growing crops of rye that are later infected with an ergot alkaloid producing fungus *Claviceps purpurea*. During infection, *C. purpurea* produces structures called sclerotia in place of the native rye grains. The sclerotia contain complex alkaloids that are derived from lysergic acid. At the flowering stage of the rye, the fungus (which has been grown for 5-6 weeks in culture) is inoculated onto the flowers of the grass. Depending on weather conditions, the sclerotia can be harvested after 4-6 weeks. Total ergot alkaloids must be extracted from the sclerotia. All the alkaloids must then be hydrolyzed in a strong base to produce lysergic acid. The second known method is to grow mutant strains of either *C. purpurea* or *Claviceps paspali* in either stationary surface cultures or submerged cultures—all containing a growth medium. There are three cultivation steps: preinoculating tanks, seed tanks, and production fermenters, each requiring a different growth medium. The cultures are grown for several weeks. Our experiences have optimum alkaloid production after 7 weeks of growth. From our experience, alkaloid production is not guaranteed in this method. Similar to the first known method, total complex alkaloids must be extracted and hydrolyzed in this second known method to produce lysergic acid before

purification of lysergic acid. The following publications describe the generalities of these known methods of producing lysergic acid: (1) Annis, S.L., and Panaccione, D.G. 1998. Presence of peptide synthetase gene transcripts and accumulation of ergopeptines in *Claviceps purpurea* and *Neotyphodium coenophialum*. Canadian Journal of Microbiology 44:80-86; (2) Coyle, C.M., Cheng, J.Z., O'Connor, S.E., Panaccione, D.G. 2010. An old yellow enzyme gene controls the branch point between *Aspergillus fumigatus* and *Claviceps purpurea* ergot alkaloid pathways. Applied and Environmental Microbiology 76:3 898-3903; and (3) Kren, V., and Cvak, L. 1999. Ergot, The Genus *Claviceps*. Harwood Academic Publishers, Amsterdam, page 518.

Unlike the known methods of producing lysergic acid as described above, the present invention provides an efficient method of producing lysergic acid and its purification directly without the need to utilize complex alkaloids.

#### SUMMARY OF THE INVENTION

The present invention provides methods for the efficient production of lysergic acid, dihydrolysergic acid, and lysergol.

Another embodiment of this invention provides a strain of fungus comprising *Aspergillus fumigatus* (*A. fumigatus*) and expressing one or more genes of the ergot alkaloid biosynthesis pathways from one or more fungus selected from the group consisting of:

- a. *Epichloë festucae* var. *lolii* x *Epichloë typhina* isolate Lp1 (*E. sp.* Lp1);
- b. *Claviceps* species;
- c. *Claviceps africana* (*C. africana*);
- d. *Claviceps gigantea* (*C. gigantea*);
- e. *Periglandula* species; and
- f. *Epichloë coenophiala*, wherein gene *easA* or gene *easM* is inactivated in said *A.*

*fumigatus*. This strain includes one or more genes of the ergot alkaloid biosynthesis that are selected from the group consisting of: *easA* and *cloA*. Preferably, the strain includes wherein said gene *easA* is inactivated in said *A. fumigatus*, and said one or more fungus is *E. sp.* Lp1. Another embodiment provides wherein the strain wherein said gene *easA* is inactivated in said *A. fumigatus*, and said one or more fungus is a *Periglandula* species or an *Epichloë coenophiala* strain that produces lysergol. More preferably, this strain includes wherein said gene *easA* is inactivated in said *A. fumigatus*, and said one or more fungi are a *Periglandula* species and *E. sp.*

Lp1, wherein said expressing gene *easA* is from a *Periglandula* species or *Epichloë coenophiala* and said expressing gene *cloA* is from *E. sp. Lp1*. Another embodiment provides the strain including wherein said gene *easA* is inactivated in said *A. fumigatus*, and said one or more fungi are a *Periglandula* species or *Epichloë coenophiala* and *E. sp. Lp1*, wherein said expressing gene *cloA* is from a *Periglandula* species or *Epichloë coenophiala* and said expressing gene *easA* is from *E. sp. Lp1*. Yet another embodiment provides the strain wherein said gene *easM* is inactivated in *A. fumigatus*, said one or more fungus is *E. sp. Lp1*, and said expressing one or more genes of the ergot alkaloid biosynthesis is *cloA*. Another embodiment includes wherein the strain includes wherein said gene *easM* is inactivated in *A. fumigatus*, said one or more fungus is *C. africana*, and said expressing one or more genes of the ergot alkaloid biosynthesis is *cloA*. Another embodiment provides the strain wherein said gene *easM* is inactivated in said *A. fumigatus*, said one or more fungus is *C. gigantea*, and said expressing one or more genes of the ergot alkaloid biosynthesis is *cloA*.

Another embodiment provides a method for producing lysergic acid comprising inactivating an ergot alkaloid biosynthesis pathway gene from the fungus *A. fumigatus* and expressing genes *easA* and *cloA* from the fungus *E. sp. Lp1*, wherein said inactivated ergot alkaloid biosynthesis pathway gene is *easA* of *A. fumigatus*.

Another embodiment provides a method for producing novel ergot alkaloids comprising inactivating an ergot alkaloid biosynthesis pathway gene from the fungus *A. fumigatus* and expressing genes *easA* and *cloA* from the fungus *E. sp. Lp1*, wherein said inactivated ergot alkaloid biosynthesis pathway gene is *easA* of *A. fumigatus*.

Another embodiment provides a method for producing dihydrolysergic acid (DHLA) comprising inactivating gene *easM* in *A. fumigatus* and expressing gene *cloA* from *E. sp. Lp1* or gene *cloA* from *C. africana* in said *A. fumigatus* strain.

Another embodiment provides a method for producing dihydrolysergol (DHlysergol) comprising inactivating gene *easM* in *A. fumigatus* and expressing one or more genes of the ergot alkaloid biosynthesis from *C. gigantea* selected from the group consisting of:

a. *cloA*; and

b. *cloA* and *easA*,

wherein said gene(s) from *C. gigantea* are expressed in said *A. fumigatus* strain.

Another embodiment of this invention provides a strain of fungus comprising a species of a fungus and expressing one or more genes of the ergot alkaloid biosynthesis pathways from one or more of said fungus, wherein said fungus has a pathway similar to *A. fumigatus*. Preferably, the strain includes wherein said one or more genes of the ergot alkaloid biosynthesis are selected from the group consisting of: *easA* and *cloA*. More preferably, the strain includes wherein said *easA* or *cloA* genes from said ergot alkaloid producing fungi are functionally similar to the genes from *Claviceps purpurea* or any of *Epichloe* species.

Another embodiment of this invention provides a method of producing ergot alkaloids in *A. fumigatus* comprising expressing ergot alkaloid synthesis genes from other fungi in *A. fumigatus easA* knockout or *easM* knockout, allowing native prenyl transferase EasL act on any ergot alkaloids so produced for producing prenylated alkaloids.

Another embodiment provides a method of producing ergot alkaloids in a strain of *A. fumigatus* comprising expressing a bidirectional *easA/easG* promoter of *A. fumigatus* to drive expression of oxidase genes in the *A. fumigatus EasA* knock-out background. Preferably, the method includes wherein said strain includes oxidase gene *cloA* from *E. sp. Lp1*. Preferably, the method includes providing a *EasA* gene from *E. sp. Lp1* that is expressed in said *A. fumigatus EasA* knock-out background. More preferably, the method includes wherein said *EasA* gene from *E. sp. Lp1* includes expression of *cloA* from *E. sp. Lp1*.

Another embodiment provides a method for the production of lysergic acid comprising providing for the expression of *EasA/CloA* in *A. fumigatus easA* knockout.

Another embodiment includes a method of producing a festuclavine-accumulating strain of *A. fumigatus* comprising a knock-out of the *easM* allele.

Another embodiment provides a method for producing lysergic acid in *A. fumigatus easA* knock-out providing amplifying *E. sp. Lp1 easA* and *E. sp. Lp1 cloA* for producing lysergic acid.

Another embodiment of this invention provides a method for accumulating lysergol comprising amplifying *easA* and *cloA* from *Periglandula* in plant material selected from the group consisting of *Stictocardia tiliifolia*, *S. beraviensis*, *Argyreia*, and *Ipomoea* species or *Epichloë coenophiala* from *Lolium arundinaceum* for accumulating lysergol.

Another embodiment provides a method for producing lysergol comprising providing expressing *Periglandula sp. easA* and *P. sp. cloA* or *Epichloë coenophiala cloA* in a *A. fumigatus easA* knock-out strain for producing lysergol.

Another embodiment provides a method for producing lysergol comprising expressing *P. sp.* easA or *Epichloë coenophiala* easA and *Epichloë sp.* Lp1 cloA in a *A. fumigatus* easA knock-out strain for producing lysergol.

Another embodiment provides a method for producing lysergol comprising *A. fumigatus* easA knock-out strain through expression of *E. sp.* Lp1 easA and *P. sp.* cloA or *Epichloë coenophiala* cloA for producing lysergol.

Preferably the methods of producing lysergol of this invention include amplifying said easA and cloA based on degenerate primers designed to anneal to versions of each gene.

Another embodiment of this invention provides a method for producing dihydrolysergic acid comprising expressing *C. africana* cloA under the control of a *A. fumigatus* easA promoter in *A. fumigatus* easM knock-out strain for producing dihydrolysergic acid.

Another embodiment of this invention provides a method for producing dihydrolysergic acid comprising expressing *C. africana* easA and *C. africana* cloA or *E. sp.* Lp1 cloA using a *A. fumigatus* easA/easG promoter for producing dihydrolysergic acid.

Another embodiment of this invention provides a method for producing dihydrolysergol comprising expressing *C. gigantea* cloA in *A. fumigatus* easM knock-out for producing dihydrolysergol. Preferably, the method includes joining said cloA to a easA promoter of *A. fumigatus* to form a cloA construct and introducing said cloA construct into *A. fumigatus* easM knock-out utilizing cotransformation with pBCphleo. More preferably, the method includes adding a *C. gigantea* easA expressed in a *A. fumigatus* easM knock-out as part of said cotransformation.

Another embodiment of this invention provides a strain of fungus comprising SEQ ID NO:4 or a strain of fungus comprising SEQ ID NO:7.

#### BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 shows the intermediates and products of the ergot alkaloid pathway (as composited from branches found in different fungi).

Fig. 2 shows ergot alkaloid synthesis (*eas*) clusters from *E. sp.* Lp1 (A) and *Aspergillus fumigatus* (B), and design of transformation construct (C).

Fig. 3 shows qualitative RT-PCR demonstrating accumulation of mRNA from indicated genes in *A. fumigatus* easA ko transformants.

Fig. 4 shows an analysis of ergot alkaloids from transformed strains of *A. fumigatus*.

Fig. 5 shows mass spectra of two unknown alkaloids with hypothesized structures.

Fig. 6 shows (A) branch points and critical steps in the biosynthesis of ergot alkaloids in different lineages of fungi; and (B) rarely encountered ergot alkaloids (prophetic) originating from mutant pathways.

Fig. 7 shows ergot alkaloid synthesis (*eas*) gene clusters from several fungi.

Fig. 8 shows dual gene expression construct for expressing *easA* and *cloA* of *E. sp. Lp1* in *A. fumigatus easA* ko. This construct was generated using fusion PCR techniques understood by those persons skilled in the art.

Fig. 9 shows analysis of ergot alkaloids from transformed strains of *A. fumigatus*.

Fig. 10 shows alternate origins of agroclavine and the origin of setoclavine.

Fig. 11 shows knockout of *easM* results in accumulation of festuclavin and eliminates fumigaclavins.

Fig. 12 shows the pathway from agroclavine to lysergic acid.

Fig. 13 shows pathway from festuclavine to dihydrolysergic acid (DHLA).

Fig. 14 shows *Aspergillus fumigatus* ergot alkaloid pathway.

#### DETAILED DESCRIPTION OF THE INVENTION

Different lineages of fungi produce distinct classes of ergot alkaloids. Lysergic acid-derived ergot alkaloids produced by fungi in the Clavicipitaceae are particularly important in agriculture and medicine. The pathway to lysergic acid is partly elucidated, but the gene encoding the enzyme that oxidizes the intermediate agroclavine is unknown. We investigated two candidate agroclavine oxidase genes from the fungus *Epichloë festucae* var. *lolii* × *Epichloë typhina* isolate Lp1 (henceforth *E. sp. Lp1*), which produces lysergic acid-derived ergot alkaloids. Candidate genes *easH* and *cloA* were expressed in a mutant strain of the mold *Aspergillus fumigatus*, which typically produces a subclass of ergot alkaloids not derived from agroclavine or lysergic acid. Candidate genes were co-expressed with the *E. sp. Lp1* allele of *easA*, which encodes an enzyme that catalyzed the synthesis of agroclavine from an *A. fumigatus* intermediate; the agroclavine then served as substrate for the candidate agroclavine oxidases. Strains expressing *easA* and *cloA* from *E. sp. Lp1* produced lysergic acid from agroclavine, a process requiring a cumulative six electron oxidation and a double bond isomerization. Strains

that accumulated excess agroclavine (as a result of *E. sp. Lp1 easA* expression in the absence of *cloA*) metabolized it into two novel ergot alkaloids for which structures were determined on the basis of mass spectra and precursor feeding studies. Our data indicate CloA catalyzes multiple reactions to produce lysergic acid from agroclavine and that combining genes from different ergot alkaloid pathways provides an effective strategy to engineer important pathway molecules and novel ergot alkaloids.

Ergot alkaloids derived from lysergic acid have impacted human lives for millennia, initially as toxins and more recently as pharmaceuticals; however, important aspects of lysergic acid biosynthesis remain unsolved. We combined genes from ergot alkaloid pathways from two fungal lineages to produce lysergic acid in the genetically tractable fungus *Aspergillus fumigatus*. In doing so, we demonstrated that a previously identified gene encodes additional activities required for lysergic acid biosynthesis. We also found that combining genes from ergot alkaloid pathways from different fungi resulted in production of completely novel ergot alkaloids. In some embodiments of the invention, controlling the ergot alkaloid pathway will facilitate production and development of pharmaceuticals for the treatment of dementia and other cognitive or neurological disorders.

Ergot alkaloids (EA) are agriculturally and pharmaceutically relevant secondary metabolites synthesized by several species of fungi. Historically, EA caused periodic mass poisonings due to infection of grain crops by the ergot fungus *Claviceps purpurea* (1). Agriculturally, EA in forage grasses colonized by endophytic *Epichloë* spp. [including many fungi recently realigned from genus *Neotyphodium* (2)] reduce weight gain and fitness in grazing animals (3, 4). Clinically, the structural similarities of EA to neurotransmitters allow EA to treat cognitive and neurological maladies including dementia, migraines, and Parkinson's disease (5–7). The neurotransmitter-mimicking activities of EA are most infamously evident in the psychoactive drug LSD, a semisynthetic EA derivative (8).

Representatives of two major families of fungi—the Clavicipitaceae and the Trichocomaceae—produce EA. All EA-producing fungi share early pathway steps before diverging to produce lineage-specific classes of EA (Fig. 1). Members of the Clavicipitaceae, including *Claviceps purpurea* or the endophytic *Epichloë* species such as *E. festucae* var. *lolii* × *E. typhina* isolate Lp1 (2, 9) (henceforth called *E. sp. Lp1*), synthesize lysergic acid-based alkaloids in which the D ring of the ergoline nucleus is unsaturated between carbons 9 and 10,

and carbon 17 is highly oxidized (Fig. 1) (4, 10, 11). EA-producing fungi in the Trichocomaceae, such as the opportunistic human pathogen *Aspergillus fumigatus*, produce clavine-based derivatives in which the D ring is saturated and carbon 17 remains reduced as a methyl group (12, 13).

The branch point of the pathway occurs during D ring closure. In *A. fumigatus*, the 8,9 double bond in chanoclavine aldehyde is reduced by the enzyme EasA, allowing the aldehyde group free rotation to interact with the secondary amine to promote ring closure via Schiff base formation (14–16). The resulting iminium ion is subsequently reduced by EasG to form festuclavine (16, 17), which may be modified at carbons 9 and/or 2 to form various fumigaclavine derivatives (Fig. 1). Most EA-producing fungi in the Clavicipitaceae, however, synthesize the 8,9 unsaturated clavine agroclavine from chanoclavine aldehyde via the activity of an alternate version of EasA that acts as an isomerase rather than a reductase (15, 17). In *C. purpurea* and *Epichloë* spp., agroclavine is oxidized to form elymoclavine, and elymoclavine is further oxidized and isomerized to form lysergic acid (Fig. 1). Lysergic acid is then incorporated into ergopeptines and/or lysergic acid amides. Lysergic acid derivatives are the EA used for pharmaceutical development, but these compounds are produced exclusively in clavicipitaceous fungi and not in model organisms that would facilitate their modification and development.

The genetics of many steps in the EA pathway has been characterized; however, the identity of the gene encoding the oxidase that converts agroclavine to elymoclavine has remained elusive. All known genes involved in ergot alkaloid synthesis (*eas* genes) in both *A. fumigatus* and the Clavicipitaceae have been found in clusters (Fig. 2) (11, 18–24). The roles of many of the genes in *eas* clusters have been determined by gene knockout or by expression of coding sequences in *Escherichia coli*. Among the genes in *eas* clusters of lysergic acid-producing fungi, two genes stand out as candidates to encode the enzyme that oxidizes agroclavine. The gene labeled *easH* encodes a product with high similarity to dioxygenases (10, 19, 25); at the time this present work was conducted, its role in the pathway had not been tested, but very recently EasH has been demonstrated to oxidize lysergyl-peptide lactams to facilitate their cyclolization to ergopeptines (25). This gene is present in both *A. fumigatus* and *Epichloë* spp.; however, the copy found in *A. fumigatus* (which lacks agroclavine and lysergic acid derivatives) is a pseudogene (10). The gene named *cloA*, for clavine oxidase (26), is a second candidate. Haarmann et al. (26) showed that CloA was required for oxidation of carbon 17 of elymoclavine

during synthesis of lysergic acid and speculated that CloA also oxidized the same carbon in agroclavine. Only fungi that produce lysergic acid-derived alkaloids contain *cloA* in their *eas* clusters (18–24).

To test each candidate gene, a heterologous expression system was designed using an *A. fumigatus easA* knock out (*easA* ko) (15) as the host strain, which allowed for precise pathway control based on insertion of an agroclavine-specific allele of *easA*. Constructs used for transformation contained three elements: *easA* from *E. sp. Lp1*, a bidirectional *easA/easG* promoter from *A. fumigatus*, and the candidate gene (either *easH* or *cloA*) amplified from *E. sp. Lp1* (Fig. 2). Co-expression of the *E. sp. Lp1* allele of *easA* in the *easA* ko background of *A. fumigatus* allows accumulation of agroclavine (15, 17), which served as substrate for the enzyme expressed from the candidate gene in the construct. This combinatorial approach allowed clear testing of the two candidate genes and identification of the gene encoding the agroclavine-oxidizing enzyme. Moreover, production of agroclavine in *A. fumigatus* allowed accumulation of novel ergot alkaloids as a result of the activity of native *A. fumigatus* enzymes on agroclavine.

## RESULTS

*Aspergillus fumigatus easA* ko was successfully transformed with constructs for expressing either *easA/easH* or *easA/cloA* of *E. sp. Lp1*. Evidence of successful transformation and expression of the *E. sp. Lp1* genes included accumulation of mRNA from both *E. sp. Lp1* genes introduced with a particular construct (Fig. 3). Further evidence of successful expression of the introduced genes was the altered ergot alkaloid profiles observed by HPLC with fluorescence detection (Fig. 4, Table 1). As described previously (15), the recipient strain, *A. fumigatus easA* ko, accumulated primarily chanoclavine and also small quantities of agroclavine [arising via a non-catalyzed keto-enol tautomerization of chanoclavine aldehyde (15)] and larger quantities of its oxidation product setoclavine. Transformants expressing *E. sp. Lp1 easA/easH* accumulated chanoclavine and significantly more agroclavine and setoclavine/isosetoclavine than did the non-transformed recipient strain, indicating successful expression of the *easA* allele of *E. sp. Lp1* without further modification of the ergot alkaloid profile by the product of *easH*. The same ergot alkaloid profile was observed in a previous study in which *C. purpurea easA* was expressed in *A. fumigatus easA* ko (15). Strains that expressed the *E. sp. Lp1 easA/cloA* construct also accumulated chanoclavine, agroclavine, and setoclavine/isosetoclavine but at levels

comparable to the parent strain *A. fumigatus easA* ko. In addition, the *easA/cloA* expressing strains accumulated a pair of polar compounds that co-eluted with lysergic acid/isolysergic acid standards (Fig. 4). The identity of the compounds as lysergic acid and its diastereoisomer was supported by LC-MS analyses in which the *easA/cloA* strains produced parent ions and fragments identical to those arising from the lysergic acid standard. These data indicate that CloA catalyzes a cumulative six electron oxidation of agroclavine to lysergic acid and that CloA or EasA isomerizes the 8,9 double bond in the D ring to the 9,10 position. Expression of constructs in which *easA* from *E. sp. Lp1* was replaced by *easA* from *Claviceps fusiformis* [a species whose pathway ends at elymoclavine and thus never isomerizes an 8,9 double bond to a 9,10 double bond (21)], still resulted in production of lysergic acid. This observation supports the hypothesis that double bond isomerase activity resides on CloA rather than EasA. The amount of lysergic acid extracted from *easA/cloA* cultures varied depending on the solvent used. Both 98% methanol + 2% acetic acid and 10% (w/v) aqueous ammonium carbonate extracted significantly more (approximately 2.5 fold) lysergic acid than did unsupplemented methanol ( $P = 0.006$ ).

In addition to known ergot alkaloids described above, strains transformed with constructs containing either *easA/easH* or *easA/cloA* fragments accumulated two novel alkaloids referred to as unknown A (unk A) and unknown B (unk B) (Fig. 4; Table 1). The *easA/easH* strain, which accumulated significantly more agroclavine and setoclavine than did the *easA/cloA* strain, also accumulated significantly greater quantities of unk A and B. Unk A fluoresced more intensely at the 272/372 nm wavelength settings than at the 310/410 nm wavelength settings, which is typical of ergot alkaloids lacking a double bond between positions 9 and 10 of the ergoline nucleus (12). In contrast unk B fluoresced ten times more intensely at 310/410 nm wavelengths than at the 272/372 nm wavelength setting, indicating the presence of a 9,10 double bond (12). LC-MS analyses revealed that unk A and B had molecular ions with masses of 307.3 and 323.2, respectively (Fig. 5). The molecular ion of unk A corresponds to the mass of [agroclavine + H]<sup>+</sup> with an additional prenyl group, whereas, the molecular ion of unk B corresponds to the mass of [setoclavine + H]<sup>+</sup> with an additional prenyl group.

To test the hypothesis that unk A and B correspond to prenylated version of agroclavine and setoclavine, agroclavine was fed to three isolates of *A. fumigatus*: 1) *easA* ko, the transformation recipient, which was derived from *A. fumigatus* isolate FGSC A1141 and contains

a functional copy of the ergot alkaloid prenyl transferase gene *easL* (27); 2) Af 293, a wild-type strain that also has a functional copy of *easL* (27); and, 3) NRRL 164, a strain unable to produce the prenylated ergot alkaloid fumigaclavine C due to a mutation resulting in a premature stop codon in *easL* (27). Agroclavine-fed cultures of all isolates contained some unmetabolized agroclavine and its oxidation product setoclavine. However, only *easA* ko and Af 293, which contain functional copies of the prenyl transferase gene *easL*, accumulated unk A and unk B (Table 2). These data are consistent with unk A and B being agroclavine and setoclavine, respectively, prenylated by the prenyl transferase encoded by *easL*.

Our results demonstrate that the P450 monooxygenase encoded by *cloA* of *E. sp. Lp1* catalyzes successive oxidations of agroclavine to produce lysergic acid. The data also suggest that CloA catalyzes the double bond isomerization, from position 8,9 to 9,10. Our strategy for testing the function of the genes *easH* and *cloA* through heterologous expression in an *A. fumigatus* background that was modified simultaneously to produce the substrate agroclavine was effective. Consistent with the data of Coyle et al. (15), both *easA/easH* and *easA/cloA* mutants produced agroclavine, as a result of expressing *E. sp. Lp1 easA*. In addition, both types of transformants accumulated setoclavine and isosetoclavine, diastereoisomers formed by the oxidation of agroclavine by endogenous peroxidases in *A. fumigatus* and dozens of other fungi and plants (15, 28, 29). However, only transformants containing the *easA/cloA* construct yielded lysergic acid. The lesser quantities of agroclavine and setoclavine observed in the *easA/cloA* transformants, compared to the *easA/easH* strains, are consistent with the *easA/cloA* strains having CloA to oxidize accumulating agroclavine. The accumulation of lysergic acid in CloA-expressing strains indicates that the enzyme performs multiple catalytic steps: a two electron oxidation of agroclavine to elymoclavine, then a pair of two electron oxidations to convert elymoclavine to lysergic acid, presumably via an undetected aldehyde intermediate (30). The role of CloA in catalyzing multiple oxidations to form paspalic acid or lysergic acid was previously hypothesized by Haarmann et al. (26). Our data also indicate that CloA catalyzes the double bond isomerization. Although a role for *E. sp. Lp1 EasA* (introduced on the same construct) in the double bond isomerization cannot be excluded, the observation that an *easA/cloA* construct containing *easA* from *C. fusiformis* (lacking lysergic acid and thus the need to isomerize the double bond in ring D) still produced lysergic acid, indicates that the double bond isomerase activity resides on CloA.

The lack of detectable elymoclavine—the first oxidation product of *cloA* acting on agroclavine—or any other intermediates in the oxidation series to lysergic acid in our positive transformants indicates that CloA may bind agroclavine and execute successive oxidations before releasing lysergic acid. The lack of detectable paspalic acid (which is the 8,9-double bond isomer of lysergic acid) in our lysergic acid-positive transformants indicates that the double bond isomerization, from position 8,9 (as in agroclavine and elymoclavine) to position 9,10 (as in lysergic acid and derivatives thereof), occurs while substrate is bound to CloA. Moreover, young cultures (<3 days old) yielded lesser quantities of lysergic acid when extracted with methanol but significantly more when extracted with acetic acid-supplemented methanol or ammonium carbonate. One interpretation of this observation is that the acid or base helped denature CloA, releasing otherwise bound product for detection.

An unexpected and important finding of this study was the accumulation of two novel alkaloids, unk A and B, from both mutants but in greater quantities in the *easA/easH* transformants, which accumulated greater concentrations of agroclavine and setoclavine. The structure of each unknown, with a prenyl group on carbon 2 of either agroclavine or setoclavine, comes from three observations. First, the elution time and fluorescence properties of each analyte were consistent with predicted properties of prenylated forms of agroclavine and setoclavine. Second, the molecular weights are consistent with either agroclavine or setoclavine, with a 68 amu moiety attached, which corresponds to the mass of a prenyl group. Finally, and most importantly, the accumulation of the compounds was restricted to strains of *A. fumigatus* that have a functional copy of the prenyl transferase FgaPT1 (encoded by the ergot alkaloid cluster gene *easL*). FgaPT1 is responsible for prenylating fumigaclavine A to fumigaclavine C (31), and the discovery of 2-prenylated versions of additional ergot alkaloids, such as 2-prenylated festuclavine and 2-prenylated fumigaclavine B (32), indicates that FgaPT1 accepts other ergot alkaloids as substrates. The *easA* ko mutant that served as the recipient in our transformations was derived from *A. fumigatus* FGSC A1141, which accumulates fumigaclavine C (27), demonstrating that it has a functional copy of *easL*. Our data demonstrates that a combinatorial approach based on expression of enzymes from a different lineage of ergot alkaloid producers in *A. fumigatus* can yield novel ergot alkaloids. Based on their structures, it is possible that unk A and unk B will have activities similar to those of fumigaclavine C, which has been shown to have anti-inflammatory activity (33).

In summation, our method of the present invention of heterologous expression of *easA* (to produce agroclavine substrate) along with candidate oxidase genes *easH* or *cloA* successfully demonstrated that *cloA* is necessary for lysergic acid production from agroclavine. The production of lysergic acid in an experimentally tractable and fast-growing organism such as *A. fumigatus* is significant because lysergic acid is used as a base for modification in numerous pharmaceutical products, including the drugs nicergoline, cabergoline, and metergoline (34). Currently, lysergic acid is mass produced by hydrolysis of more complex ergot alkaloids or isomerization of paspalic acid obtained from two-stage fermentation cultures or from ergots obtained from inoculated plants (34). In contrast, our *easA/cloA* mutant produces lysergic acid directly. In addition, *A. fumigatus* has the potential to be a better industrial fungus in terms of growth rate and ease of genetic manipulation. Therefore, the *easA/cloA* mutant of this invention is of industrial use in providing a more direct means of producing lysergic acid or derivatives thereof.

#### METHODS AND MATERIALS

Preparation of transformation constructs. Each candidate oxidase gene (*easH* or *cloA*) was incorporated into a three-component construct that contained a bidirectional promoter from *A. fumigatus* (originating from the divergently transcribed genes *easA* and *easG*) centered between the candidate oxidase gene from *E. sp. Lp1* and the allele of *easA* from *E. sp. Lp1* (Fig. 2). The bidirectional promoter drove expression of both the candidate oxidase gene and *E. sp. Lp1 easA*. The *easA* allele was included to generate agroclavine as substrate for the product of the candidate gene. Constructs were generated by fusion PCRs.

Fungal transformation. Candidate oxidase constructs were co-transformed into *A. fumigatus easA* ko (15), along with the selectable marker pAMD1, which contains the acetamidase gene of *Aspergillus nidulans* (35). Transformants capable of utilizing acetamide as a source of nitrogen were selected on acetamide medium (36). The transformation protocol was based on previously described methods (15, 18).

mRNA analysis. Cultures were grown in 50 mL of malt extract broth (Difco, Detroit, MI) in a 250 mL flask for 1 day while shaking at 80 rpm at 37 °C to form a mat of hyphae on the surface of the broth. The mat was transferred to an empty Petri dish and incubated at 37 °C for an additional day to promote conidiation. RNA was extracted from approximately 100 mg of conidiating colony with the Plant RNeasy kit (Qiagen, Gaithersburg, MD), treated with DNaseI

(Qiagen), and reverse transcribed with Superscript II (Invitrogen, Carlsbad, CA). The presence of transcripts from individual genes was tested by PCR with gene-specific primers. The absence of genomic DNA in individual cDNA preps was confirmed by priming amplification with oligonucleotides that flank an intron.

Alkaloid analysis. For quantitative analyses, colonies were grown on malt extract agar [15 g malt extract + 15 g agar per L] for 11 days. Samples of approximately 50 mm<sup>2</sup> surface area were collected with the broad end of a 1000- $\mu$ L pipet tip. Unless otherwise indicated, alkaloids were extracted with 98% methanol + 2% acetic acid at 55 °C for 30 min. Alternate extractions were conducted with 100% methanol or 10% aqueous ammonium acetate. Conidia in each extract were counted to provide an estimate of fungal biomass. Extracts clarified by centrifugation were then analyzed by reverse-phase HPLC with fluorescence detection (12). Lysergic acid standard was prepared by hydrolyzing 1 mg of ergotamine tartrate (Sigma-Aldrich, St. Louis, MO) in 100  $\mu$ L of 1.2 M NaOH at 75 °C for 6 hr, followed by neutralization with a 1.2 M solution of HCl, purification on a C18 SPE column (Biotage, Charlotte, NC), and verification by LC-MS. Chanoclavine was obtained from Alfarma (Prague, Czech Republic), agroclavine was obtained from Fisher (Pittsburgh, PA), and setoclavine was prepared by oxidizing agroclavine as previously described (28, 29). Quantities of alkaloids among strains were compared by ANOVA and, when ANOVA indicated a significant effect of fungal strain on alkaloid quantity ( $P < 0.05$ ), means were separated by a Tukey-Kramer test. Statistical analyses were performed with JMP (SAS, Cary, NC). For LC-MS analysis, cultures were grown for 1 week on malt extract agar. Conidiating cultures were washed repeatedly with 4 mL of HPLC-grade methanol. After pelleting conidia and mycelia by centrifugation, the supernatant was concentrated to 100  $\mu$ L in a speedvac, and 10  $\mu$ L was analyzed by LC-MS as described previously (37).

Precursor feeding study. The ability of strains of *A. fumigatus* to convert agroclavine or setoclavine into unk A or B was tested by feeding agroclavine to the following *A. fumigatus* strains: NRRL 164, which lacks a functional copy of *easL*, and *easA* ko and Af 293, which have functional copies of *easL* (27). Six replicate cultures of each strain were grown from 60,000 conidia in 200  $\mu$ L of malt extract broth in a 2-mL microcentrifuge tube. Cultures were supplemented with 37 nmol of agroclavine in 1  $\mu$ L of methanol or with 1  $\mu$ L methanol as a control. An additional control was malt extract broth without conidia but with 1  $\mu$ L of agroclavine (37 nmol). The cultures were incubated for 1 week at 37 °C and then extracted by

the addition of 300  $\mu$ L of methanol along with ten 3-mm diameter glass beads followed by bead-beating in a Fastprep 120 (Bio101, Carlsbad, CA) at 6 m/s for 30 s. Alkaloids were analyzed by HPLC with fluorescence detection as described above.

The above research with lysergic acid was conducted with licenses from the West Virginia Board of Pharmacy (TI0555042) and the US Drug Enforcement Agency (RP0463353).

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## FIGURES 1-5 and 9-14 LEGENDS

Fig. 1 shows intermediates and products of the ergot alkaloid pathway (as composited from branches found in different fungi). The role of different alleles of *easA* (isomerase versus reductase encoding types) in controlling the branch point is indicated. Alkaloids with a 9,10 double bond (e.g., setoclavine and lysergic acid and its derivatives) often occur as diastereoisomers at position 8). Roles for genes discussed in text or illustrated in Fig. 2 are indicated. Double arrows indicate one or more omitted intermediates. Insert shows ring and position labeling referred to in text. DMAPP, dimethylallylpyrophosphate.

Fig. 2 shows ergot alkaloid synthesis (*eas*) clusters from *E. sp. Lp1* (Figure 2A) and *Aspergillus fumigatus* (Figure 2B), and design of transformation construct (Figure 2C). Figure 2A shows *Epichloë sp. Lp1 eas* cluster redrawn from Schardl et al. (2013b); AT rich repeat regions (15 to 25 kb each) were compressed in the diagram to facilitate the presentation. Figure 2B. shows *Aspergillus fumigatus eas* cluster redrawn from Coyle and Panaccione (2005);  $\Psi$  = pseudogene. Genes unique to the *E. sp. Lp1* cluster are shown in black, and those unique to the *A. fumigatus* cluster are indicated in white. Genes common to both clusters are shown in gray. Although both clusters contain an allele of *easA*, the products of those alleles differ functionally, and so they differ in shading in their respective clusters. Figure 2C shows general design of constructs generated by fusion PCR. Candidate genes were *cloA* or *easH* from *E. sp. Lp1*. Black and white fragments correspond to *E. sp. Lp1* or *A. fumigatus* origin, as above.

Fig. 3 shows a qualitative RT-PCR demonstrating accumulation of mRNA from indicated genes in *A. fumigatus easA* ko transformants. Horizontal strain labels: *easA* ko refers to non-transformed recipient stain; and, *easA/cloA* or *easA/easH* refer to transformants. Vertical gene labels refer to the *E. sp. Lp1* gene for which amplification was attempted in that lane. Each cDNA preparation was diluted 1:1000 prior to amplification. Scale at left indicates the relative mobility of relevant fragments from *BstEII*-digested bacteriophage lambda.

Fig. 4 shows an analysis of ergot alkaloids from transformed strains of *A. fumigatus*. Samples were analyzed with two fluorescence detectors; excitation and emission wavelengths are indicated. Lysergic acid and other ergot alkaloids with a 9,10 double bond fluoresce more strongly at 310 nm/410 nm conditions, whereas other ergot alkaloids fluoresce maximally with settings of 272 nm/372 nm (Panaccione et al., 2012). Ergot alkaloids with 9,10 double bonds form diastereoisomers at carbon 8. Values for both diastereoisomers were added in quantitative

analyses. Strain names and line colors are indicated in key. Abbreviations: LA, lysergic acid; ILA, isolysergic acid; IS, isosetoclavine; S, setoclavine; UB, unknown B, Ch, chanoclavine; Ag, agroclavine; UA, unknown A.

Fig. 5 shows mass spectra of two unknown alkaloids with hypothesized structures. Spectra were collected from LC-MS analyses with electrospray ionization in positive mode. Further evidence of prenylation is presented in Table 2.

Fig. 9 shows the analysis of ergot alkaloids from transformed strains of *A. fumigatus*. Samples were analyzed with two fluorescence detectors; excitation and emission wavelengths are indicated. Lysergic acid and other ergot alkaloids with a 9, 10 double bond fluoresce more strongly at 310 nm/410 nm conditions, whereas other ergot alkaloids fluoresce maximally with settings of 272 nm/372 nm (Panaccione et al., 2012). In protic solvents, lysergic acid forms diastereoisomers (with isolysergic acid) at C8. Values for both diastereoisomers were added in quantitative analyses. Strain names and line colors are indicated in key. Abbreviations: LA, lysergic acid; ILA, isolysergic acid; S, setoclavine; Ch, chanoclavine; Ag, agroclavine.

Fig. 10 shows alternate origins of agroclavine and origin of setoclavine. Pathway spurs leading to setoclavine are indicated in green. When *easA* is knocked out, chanoclavine aldehyde that accumulates can keto-enol tautomerize. Tautomers that resolve with the aldehyde in close proximity to the secondary amine can undergo ring closure via Schiff base formation. The resulting iminium ion (Fig. 6) is reduced by *EasG* to form agroclavine (Coyle et al., 2010). Agroclavine that accumulates can be oxidized at C8 to form setoclavine by non-specific peroxidase activity present in many organisms (e.g., Béliveau and Ramstad, 1967; Panaccione et al., 2003; Coyle et al., 2010).

Fig. 11 shows fluorescence HPLC chromatogram showing festuclavine (F) accumulating to higher concentration in *easM* ko strain and lack of pathway end product fumigaclavine C in the *easM* ko.

Fig. 12 shows a pathway from agroclavine to lysergic acid. Double arrow: aldehyde intermediate omitted.

Fig. 13 shows a pathway from festuclavine to dihydrolysergic acid (DHLA). Double arrow: aldehyde intermediate omitted.

Fig. 14 shows ergot alkaloid pathway of *Aspergillus fumigatus*. Roles for genes are indicated between intermediates or products. Double arrow indicates one or more ncharacterized

intermediates: DMAPP, dimethylallylpyrophosphate; DMAT, dimethylallyltryptophan; Trp, tryptophan.

Table 1: Ergot alkaloid accumulation (amol/conidium) in cultures of modified strains of *A. fumigatus*<sup>a</sup>

Strain	chano clavine	lysergic acid <sup>b</sup>	agroclavine	setoclavine <sup>b</sup>	unknown A	unknown B
<i>easA</i> ko	0.42 ± 0.04	n.d.	0.055 ± 0.01 B	0.16 ± 0.01 B	n.d.	n.d.
<i>easA/cloA</i>	0.58 ± 0.1	1.0 ± 0.1	0.27 ± 0.04 B	0.60 ± 0.07 B	0.16 ± 0.04 B	0.062 ± 0.01 B
<i>easA/easH</i>	0.59 ± 0.07	n.d.	0.81 ± 0.1 A	2.0 ± 0.2 A	0.38 ± 0.06 A	0.22 ± 0.05 A

<sup>a</sup> Data are means of six samples ± standard error; means followed by a different letter within a column differ significantly ( $\alpha=0.05$ ) in a Tukey-Kramer test.

<sup>b</sup> Values calculated from sums of both diastereoisomers.

Table 2: Ergot alkaloids (nmol per culture) in strains fed 37 nmol agroclavine and controls<sup>a</sup>

strain/treatment	agroclavine	setoclavine <sup>b</sup>	unknown A	unknown B
Af 293/agroclavine	22 ± 1 B	2.5 ± 0.1 A	0.56 ± 0.04 A	0.040 ± 0.001 A
NRRL 164/agroclavine	24 ± 2 B	2.1 ± 0.2 AB	n.d.	n.d.
<i>easA</i> ko/agroclavine	21 ± 0.3 B	1.9 ± 0.08 B	0.22 ± 0.03 B	0.0078 ± 0.0007 B
medium/agroclavine	31 ± 0.5 A	0.89 ± 0.05 C	n.d.	n.d.
Af 293/methanol	n.d.	n.d.	n.d.	n.d.
NRRL 164/methanol	n.d.	n.d.	n.d.	n.d.
<i>easA</i> ko/methanol	0.041 ± 0.002 C	0.0023 ± 0.0003 D	n.d.	n.d.

<sup>a</sup> Data are means of six samples ± standard error; means followed by a different letter within a column differ significantly ( $\alpha=0.05$ ) in a Tukey-Kramer test.

<sup>b</sup> Values calculated from sums of both diastereoisomers.

## SPECIFIC EMBODIMENTS OF THIS INVENTION

We combined genes from ergot alkaloid pathways from two fungal lineages to produce lysergic acid in the genetically tractable fungus *Aspergillus fumigatus*. In doing so, we

demonstrated that a previously identified gene encodes additional activities required for lysergic acid biosynthesis. This unique expression platform will allow for testing of the functions of additional alleles of these key genes in the pathway to lysergic acid. Our data indicate that the enzymes involved have unique multifunctional capabilities. CloA catalyzes successive oxidations at C17 and also may catalyze a double bond isomerization. Alternatively, the isomerase form of EasA, which catalyzes an isomerization activity critical for closure of the fourth and final ring of the ergoline nucleus, may catalyze the double bond isomerization. Our *in vivo* approach allows testing of the functions of genes without needing to rely on *in vitro* expression of the P450 monooxygenase encoded by *cloA*. Our *in vivo* expression platform provides the method for production of additional and novel ergot alkaloids.

### I. Background

Representatives of two major families of fungi—the Clavicipitaceae and the Trichocomaceae—produce ergot alkaloids. All ergot alkaloid-producing fungi share early pathway steps before diverging to produce lineage-specific classes of ergot alkaloids (Panaccione, 2005) (Fig. 6). Several ergot alkaloid-producing members of the Clavicipitaceae including *Claviceps purpurea*, *C. paspali*, several *Epichloë* species [such as *E. festucae* var. *lolii* × *E. typhina* isolate Lp1 (Schardl et al., 1994; Leuchtman et al., 2014) (henceforth called *E. sp. Lp1*)], and several *Periglandula* species synthesize lysergic acid-based alkaloids in which the D ring (fourth or last ring to form) of the ergoline nucleus is unsaturated between carbons 9 and 10, and carbon 17 is highly oxidized (Fig. 1)(reviewed in Schardl et al., 2006; Lorenz et al., 2009; Panaccione et al., 2014). Two exceptional members of the Clavicipitaceae—*C. africana* and *C. gigantea*—produce dihydroergot alkaloids (DHergot alkaloids), which lack the double bond in the D ring but still may be oxidized or substituted at carbon 17 (Agurell, 1966; Barrow et al., 1974). In the other lineage (Trichocomaceae) are a few fungi such as *Aspergillus fumigatus* that produce clavine-based ergot alkaloids (festuclavine and fumigaclavines) in which the D ring is saturated and carbon 17 remains reduced as a methyl group (Wallwey and Li, 2011; Panaccione et al., 2012) (Fig. 1). Several of the lysergic acid derivatives and DHergot alkaloids of the Clavicipitaceae are valued for their pharmacological activity and used as described above (see Significance section; Table 1). The fumigaclavines of *A. fumigatus* have not been used clinically.

The first branch point of the pathways found in these two fungal lineages occurs during D ring closure. In *A. fumigatus*, *C. africana*, and *C. gigantea*, the 8,9 double bond in chanoclavine

aldehyde is reduced by the enzyme EasA, allowing the aldehyde group free rotation to interact with the secondary amine to promote ring closure via Schiff base formation (Coyle et al., 2010; Cheng et al., 2010b; Wallwey et al., 2011). The resulting iminium ion is subsequently reduced by EasG to form festuclavine (Wallwey et al., 2010; Cheng et al., 2010b). Most common ergot alkaloid-producing fungi in the Clavicipitaceae, however, diverge from *A. fumigatus* at the first branch point and synthesize the 8,9 unsaturated clavine agroclavine from chanoclavine aldehyde via the activity of an alternate version of EasA that acts as an isomerase rather than a reductase (Coyle et al., 2010; Cheng et al., 2010b). In *C. purpurea*, *C. paspali*, and *Epichloë* spp., agroclavine is oxidized at C17 to form elymoclavine, and elymoclavine is further oxidized and isomerized to form lysergic acid (Fig. 1). Lysergic acid is then incorporated into ergopeptines and/or lysergic acid amides. Our *easA* knockout strain (*easA* ko) of *A. fumigatus* (Coyle et al., 2010) provides an excellent background for reprogramming of the *A. fumigatus* ergot alkaloid pathway to a lysergic acid-based pathway. Figure 6 shows (A) branch points and critical steps in the biosynthesis of ergot alkaloids in different lineages of fungi, and (B) rarely encountered ergot alkaloids originating from mutant pathways.

A second branch point—this one between members of the Trichocomaceae such as *A. fumigatus* and the DHergot alkaloid producers *C. africana* and *C. gigantea*—occurs after formation of festuclavine. In *A. fumigatus* and relatives, festuclavine may be modified at carbons 9 and/or 2 to form various fumigaclavine derivatives (Fig. 1). Alternatively, in *C. africana* and *C. gigantea*, festuclavine is oxidized at C17 and, in the case of *C. africana*, incorporated into more complex dihydroergot alkaloids. Our *easM* ko of *A. fumigatus* provides an ideal background for analysis of pathway genes downstream from festuclavine in the DHergot alkaloid producers *C. africana* and *C. gigantea*.

Another important background point to emphasize is that genes involved in ergot alkaloid biosynthesis are clustered in the genomes of the producing fungus (Fig. 7). These gene clusters (referred to as *eas* clusters for ergot alkaloid synthesis) contain core genes that are conserved among all ergot alkaloid producers as well as lineage-specific genes required for producing the unique alkaloids found in different fungi. The clusters of *C. purpurea*, *C. paspali*, and the more distantly related *P. ipomoeae* (Schardl et al., 2013a), *Metarhizium robertsii* (formerly *Metarhizium anisopliae*), and *M. acridum* (Gao et al., 2011) are well conserved in terms of relative gene order and orientation. The clusters of *Epichloë* spp. show much more variability in

gene order and orientation; the variability may be related to interspersions of numerous transposable elements in the *eas* clusters of these *Epichloë* spp. (Schardl et al., 2013a). In the Trichomocaceae ergot alkaloid biosynthesis genes also are clustered but the order and orientation differs from that observed in the Clavicipitaceae (Panaccione and Coyle, 2005; Unsold and Li, 2005; Wallwey and Li, 2011). Genes shown in Figure 7 that are in heavy black print represent genes that are common to all ergot alkaloid producers. Other genes are involved in incorporating lysergic acid into ergopeptines. Other genes are thought to be required for assembling of a specific lysergic acid amide. While other genes are unique to *A. fumigatus*.

#### AN EMBODIMENT OF THE PRESENT INVENTION

##### Reprogramming *A. fumigatus* to produce lysergic acid (LA) via exchange of *easA* alleles and addition of *cloA*

Our previous work showed that different lineages of ergot alkaloid producers carry different alleles of *easA* that determine the first branch point of the ergot alkaloid pathway (Coyle et al., 2010). By expressing the allele of *easA* found in *C. purpurea* (Coyle et al., 2010), *Epichloë festucae* var. *lolii* (formerly *Neotyphodium lolii*) (Cheng et al., 2010b), or *E. sp. Lp1* (Robinson and Panaccione, 2014) in *A. fumigatus* in which its native *easA* allele is knocked out (*A. fumigatus easA ko*), we have engineered *A. fumigatus* to produce agroclavine as opposed to festuclavine, which starts *A. fumigatus* down the pathway to LA-based ergot alkaloids (refer to Fig. 6). We used the bidirectional *easA/easG* promoter of *A. fumigatus* to drive expression of each of several candidate oxidase genes (*easD*, *easH*, or *cloA* from *E. sp. Lp1*) along with expression of the isomerase allele *easA* from *E. sp. Lp1* (Fig. 8) in the *A. fumigatus easA ko* background. Strains expressing EasA/EasD or EasA/EasH accumulated agroclavine (as a result of expression of the isomerase allele of *easA*) but strains expressing EasA/CloA produced lysergic acid and its diastereoisomers isolysergic acid (Fig. 9). The data demonstrate that the ergot alkaloid cluster gene *cloA* encodes an enzyme that catalyzes all the oxidations of agroclavine to lysergic acid (Fig. 9). Moreover, since only lysergic acid (and not its 8,9 double bond isomer paspalic acid) was produced in our EasA/CloA strain, the double bond isomerization is catalyzed by one of the expressed enzymes (EasA or CloA) as opposed to happening spontaneously over time. The EasA/CloA strain of *A. fumigatus easA ko* is the first fungus known to produce lysergic acid as its biosynthetic endpoint in culture, and our data clearly show that expression of two genes from a lysergic acid-producing fungus is sufficient (in

conjunction with the product of the native allele of *easG* in *A. fumigatus*) to produce lysergic acid from the common pathway intermediate chanoclavine aldehyde. In this particular study, we could not distinguish CloA or EasA as the source of the double bond isomerase activity because of the need to express EasA to produce agroclavine as substrate for CloA; however, in the proposed project we will distinguish EasA or CloA as the source of double bond isomerase activity by reciprocally pairing genes from different sources.

The ergot alkaloid profiles of the strains shown in Fig. 9 require a more detailed explanation. Analyses of *A. fumigatus easA* ko (even without expression of or *E. sp. easA* allele) shows that it accumulates small quantities of agroclavine (Fig. 9). This agroclavine likely derives from keto-enol tautomerization of chanoclavine aldehyde, which builds up in this strain in the absence of a functional EasA. The enol tautomer can rotate around C8 and then tautomerize back to the aldehyde form. After this isomerization, D ring formation may occur as described above (via Schiff base formation and reduction by EasG). Agroclavine that accumulates is readily oxidized at C8 to form setoclavine by non-specific peroxidases from many sources (Beliveau and Ramstad, 1967; Panaccione et al., 2003; Coyle et al., 2010)]. The presence of agroclavine in *easA* ko and setoclavine in *easA* ko or its lysergic acid-producing derivative are explained in Fig. 10 and its legend.

Engineering of festuclavine-accumulating strain of *A. fumigatus* to serve as host for studies on dihydroergot alkaloid biosynthesis by knockout of *eas*

Whereas the *easA* knockout of *A. fumigatus* is the ideal recipient strain for expression studies designed to elucidate the origins of paspalic acid and lysergol, to study genes involved in dihydroergot alkaloid synthesis, the ideal recipient strain should accumulate festuclavine, which is the reduced analog of agroclavine and will serve as substrate for genes involved in dihydroergot alkaloid biosynthesis. We have already prepared such a strain by knocking out gene *easM* of *A. fumigatus*. Sequence data indicate that *easM* encodes a P450 monooxygenase, and our knockout data demonstrate that this enzyme is required for oxidizing festuclavine into downstream fumigaclavines (Fig. 11). In the *easM* knockout, festuclavine accumulates and no downstream fumigaclavines are produced. In some embodiments of the invention, a strain of *A. fumigatus* with a knockout of gene *easM* will be used.

### Disarming of *A. fumigatus*

Since *A. fumigatus* is an opportunistic pathogen, any strain that may eventually be used commercially must be disarmed by knocking out a virulence gene. We have knocked out *alb1* (Tsai et al., 1999) which encodes a polyketide synthase required for melanin biosynthesis and virulence in *A. fumigatus*. The albino nature of the mutants provides a convenient visual marker for these strains as well. We have made this mutation in the *A. fumigatus easA* ko background. In certain embodiments of the invention, a strain of *A. fumigatus* with a knockout *alb1* in the *easM* ko background will be used. We have routinely used acetamidase (Hynes et al., 1983) as a third selectable marker for transformation in *A. fumigatus*, allowing a round of manipulations beyond those described in manipulating the ergot alkaloid pathway (which require hygromycin and phleomycin resistance markers).

### Methods for genome sequencing that will support both specific aims:

#### General methods:

In specific embodiments of the invention, specific ergot alkaloid biosynthesis genes from various *Claviceps* or *Periglandula* species, or in some cases *E. sp. Lp1*, are amplified to produce unique ergot alkaloids, fuse those genes to *A. fumigatus* promoters, and express them in one of two different *A. fumigatus* mutant backgrounds (*easA* ko or *easM* ko). These mutant backgrounds do not complete the typical *A. fumigatus* pathway but instead accumulate substrates for the enzymes encoded by the introduced genes. These include routine molecular biology work and PCR, as well as fusion PCR for preparing promoter-coding sequence constructs for transformation (e.g., Fig. 8). We routinely transform *A. fumigatus* with three different selectable markers (hygromycin resistance, phleomycin resistance, and acetamide utilization as a nitrogen source). We have extensive experience with analyzing ergot alkaloids from *A. fumigatus* and other fungi by fluorescence HPLC (e.g., Figs. 9 and 10) and LC/MS (e.g., Panaccione and Coyle, 2005; Coyle and Panaccione, 2005; Panaccione et al., 2006; Coyle et al., 2010; Goetz et al., 2011; Robinson and Panaccione, 2012; Panaccione et al., 2012; Ryan et al., 2103).

#### Genome sequencing

Considering the current low price of genome sequencing, the small size of fungal genomes (~40 Mb), and extensive information on ergot alkaloid gene clusters available for comparison (Schardl et al., 2013ab), in some embodiments of the invention, the genomes of the fungi are sequenced. This sequencing can be done quickly in a single MiSeq flow cell. Having sequence data available offers several advantages over the alternate approach of using existing sequences of related genomes to prepare degenerate primers to clone genes of interest, then (in some cases) relying on TAIL-PCR to acquire flanking regions, and finally sequencing assembled clones, stepwise, with Sanger technology. One advantage is that we will be able to prepare specific primers to amplify the relevant genes directly, rather than taking the steps outlined in the previous sentence, thus allowing us to avoid pitfalls and also save time and money when all the genes from several fungi are considered. A second advantage is that we will obtain information about all genes in each fungus's ergot alkaloid gene cluster. A third advantage is that the genome sequences will strengthen the institutional capacity for research as well as that of the greater fungal toxin research community. The genomes of the *Periglandula* species were not sequenced herein because those fungi are obligate symbionts of plants, and their genomes are present in a relatively low proportion compared to that of the more complex genomes of their plant hosts. We already have access to sequence data from one exceptional *Periglandula* species—*P. ipomoeae*—which grows superficially on leaves such that its hyphae are separable from plant tissue (Schardl et al., 2013a).

Barcoded libraries of genomes of haploid fungi *C. paspali* NRRL 3080, *C. africana*, and *C. gigantea* may be prepared with the Illumina TruSeq kit and sequenced to approximately 50-fold coverage in a single MiSeq flow cell at the University of Kentucky Advanced Genomics Technology Center [which has led sequencing efforts on 19 other fungi with ergot alkaloid synthesis clusters (Schardl et al., 2013ab)]. The MiSeq platform offers the advantage of relatively long reads (2 x 250 nt per cluster) and 15 million clusters per flow cell. Estimating a mean genome size of 38 Mb for each of the *Claviceps* spp. [based on the mean genome size of *C. purpurea*, *C. fusiformis*, and *C. paspali* RRC-1481 (Schardl et al., 2013a)], we should achieve approximately 50-fold coverage for each genome. Genomes will be assembled with Newbler or, if the number of read is too great for that program, CLCBio from CLC Genome Workbench. Assembled genomes will be queried with sequences from homologues of *easA*, *cloA*, and other

ergot alkaloid synthesis genes available from *C. purpurea*, *C. paspali* RRC-1481, several *Epichloë* species, and *Periglandula ipomoeae*.

#### Biosynthetic origin of lysergol (prophetic):

Lysergol is the delta 9,10 double bond isomer of elymoclavine. Elymoclavine (an isomer of lysergol carrying an 8,9 double bond) is the first oxidation step in the oxidation series of agroclavine into lysergic acid. Lysergol appears to be a biosynthetic dead end, as it cannot be further oxidized to lysergic acid (Maier et al., 1988; Groger and Floss, 1997). These observations indicate that after isomerization of the double bond from the 8,9 to the 9,10 position, CloA is not able to further oxidize C17, and that in a fully functioning pathway, double bond isomerization takes place after oxidation.

Fungi that accumulate lysergol clearly have the enzymatic capacity to isomerize the double bond but appear to do so prematurely such that isomerization occurs when C17 is at a preliminary oxidation state. Once lysergol forms it cannot be further oxidized (Gröger and Floss, 1997; Maier et al., 1988).

#### Testing lysergol:

In some embodiments of the invention, alleles of *easA* and *cloA* are amplified from *Periglandula* species, which are symbiotic fungi associated with high lysergol-producing morning glory species. We have infected plant material from *Stictocardia tiliifolia*, *S. beraviensis*, and *Argyria speciosa* each of which accumulates lysergol such that it comprises >98% of the total ergot alkaloid yield (see Table 3 set forth below). We also have several accessions of *Ipomoea parasitica* in which lysergol comprises >50% of the total ergot alkaloid yield.

Table 3. Lysergol and other ergot alkaloids ( $\mu\text{g/g}$  seed) extracted from morning glory symbiota

Plant (accession)	chanoclavine <sup>1</sup>	lysergol	ergopeptines <sup>2</sup>	proportion lysergol	PCR of fungal genes
<i>Stictocardia tiliifolia</i>	0	276	0	1.0	n.a. <sup>3</sup>
<i>S. beraviensis</i> 323	0	623	0	1.0	n.a.
<i>S. beraviensis</i> 324	5	1510	0	>0.99	yes
<i>Argyria speciosa</i>	1	38	0	0.98	n.a.

<i>Ipomoea parasitica</i> 630	254	978	675	0.51	n.a.
<i>I. parasitica</i> 674	152	551	199	0.61	n.a.

<sup>1</sup> early pathway intermediate that frequently accumulates (Fig. Y)

<sup>2</sup> sum of ergobalansine and ergosine

<sup>3</sup> not attempted

Because of their obligately symbiotic nature, the *Periglandula* spp. associated with high lysergol-yielding morning glories will not be sequenced. Instead isolated mixed fungus-plant DNA directly from infected plant material with Zymogen kit may be used successfully for this purpose. In our preferred approach to amplify the entirety of the *cloA* locus, PCR can be primed from a primer designed to anneal near the 3'-end of the coding sequences of *lpsB* and another designed to anneal near the 3'-end of the coding sequences of *easC*. These two genes flank *cloA* in the *eas* clusters of *P. ipomoeae*, *C. paspali* RRC-1481, and *C. purpurea* (Fig. 7), as well as in more distantly related members of the Clavicipitaceae *Metarhizium robertsii* (formerly classified as *M. anisopliae*) and *Metarhizium acridum* (Gao et al., 2011). (*Eas* clusters from *Metarhizium* spp. are not pictured in Fig. 7, but they are identical in gene composition, order, and orientation with that of *C. paspali* RRC-1481.) The PCR product (expected to be 5 kb) can be Sanger sequenced, synthesizing new primers for successive steps. The complete *easA* gene can be amplified from primers designed to anneal near the 5'-ends of the coding sequences of *lpsB* and *lpsC* which flank *easA* in the diverse genomes listed immediately above, and Sanger sequenced. An alternate approach to cloning these genes is outlined under alternate plans lysergol set forth below. A further alternative is to express alleles of *easA* and *cloA* from an isolate of *Epichloë coenophiala* which produces lysergol and for which genome sequence is available. Coding sequences and 3'UTRs of *cloA* and *easA* can be fused to the bidirectional *easA/easG* promoter of *A. fumigatus* (Fig. 8) in combination with the alleles of the alternate gene from *E. sp. Lp1* by fusion PCR. The *E. sp. Lp1* alleles represent alleles from a pathway able to complete all required steps to lysergic acid from agroclavine. In some embodiments of the invention, the following combinations of alleles are expressed in *A. fumigatus easA* ko,

*Periglandula* sp. *easA* and *P. sp. cloA*

*P. sp. easA* and *Epichloë* sp. Lp1 *cloA*

*E. sp. Lp1 easA* and *P. sp. cloA*

*Epichloë coenophiala easA* and *Epichloë coenophiala cloA*

Translational implications (lysergol):

Lysergol can be used directly for synthesizing the pharmaceutically important ergot alkaloids nicergoline and pergolide. A cultivable source of lysergol is useful for preparation of pharmaceuticals that are derived from lysergol and also is useful in engineering of novel compounds. Lysergol is not a controlled substance, simplifying the conduct of business, and it cannot be as easily adapted to illicit drug manufacturing as lysergic acid.

Alternate plans (lysergol):

The lysergol experiments are the most demanding from a technical perspective, because we will not have direct sequence data for the fungi. Only one *Periglandula* species has been sequenced, but its *eas* cluster and *eas* sequences match well with those of *Claviceps* and *Metarhizium* spp. (Schardl et al., 2013a). Our primary strategy for cloning *easA* and *cloA* is based on the assumption that clusters will be organized the same as in *P. ipomoeae* (and as they are in *Claviceps* and *Metarhizium* spp.). In certain embodiments of the invention, conserved internal regions of *easA* and *cloA* will be amplified based on degenerate primers designed to anneal to most versions of each gene. Then the remainders of each coding sequence and some 3'-UTR can be amplified by TAIL-PCR (Singer and Burke, 2003; Liu et al., 2005; Liu and Chen, 2007). We have already cloned internal portions of other genes from the *P. sp.* symbiont of *S. beraviensis* with degenerate primers.

The biosynthetic origin of dihydroergot alkaloids:Biosynthetic origin of dihydrolysergic acid (DHLA)(prophetic):

*Claviceps africana* produces DHLA-derived ergot alkaloids such as dihydroergosine. The reduction of the 8,9 double bond to the reduced dihydro state appears to occur after the chanoclavine stage and before or during closure of the D ring (to yield festuclavine, in this case) (Barrow et al., 1974). We have DNA from *C. africana* and have used it to successfully clone the *easA* gene (sequence appears in supplement to Cheng et al., 2010b) by PCR with degenerate primers based on sequence data from other *Claviceps* spp. We also have prepared a recipient strain of *A. fumigatus* that accumulates the dihydrolysergic acid precursor festuclavine by knocking out the P450 monooxygenase gene *easM* (Bilovol and Panaccione, unpublished data;

Section II. B). Festuclavine is the 8,9 reduced version of agroclavine and should serve as substrate for versions of CloA that are capable of producing DHLA through a series of oxidations at C17 (Fig. 13). The idea that CloA from a lysergic acid producer will accept the dihydroergot alkaloid festuclavine as substrate (as opposed to its typical, delta-8,9 substrate agroclavine) is supported by the observations that the next enzyme in the pathway of lysergic acid producers, lysergyl peptide synthetase 2 (encoded by *lpsB*) accepts dihydrolysergic acid with a  $K_m$  similar to which it acts on lysergic acid (Riederer et al., 1996).

#### Testing DHLA:

We have generated a strain of the fungus *A. fumigatus* that produces festuclavine as its biosynthetic end point by knockout of the *A. fumigatus* gene *easM*. This festuclavine accumulator may serve as recipient for transformations, because festuclavine is the intermediate oxidized to DHLA in the DHLA-based pathway of *C. africana* (Barrow et al., 1974). In some embodiments of the invention, the expression of *cloA* of *E. sp. Lp1* is under the control of the *A. fumigatus easA* promoter for the production of DHLA. In other embodiments of the invention, *cloA* is amplified from the DHLA producer *C. africana* and express it in *A. fumigatus easM* ko under the control of the *A. fumigatus easA* promoter. The coding sequences and ~300 bp or 3'-UTR can be PCR amplified from *C. africana* based on specific primers designed based on genomic sequence data.

#### Translational implications (DHLA):

Dihydrolysergic acid is a preferred starting point for the synthesis of most of the major pharmaceutically important ergot alkaloids (with the exception of bromocriptine). Direct production of the compound (as opposed to purifying it after hydrolysis of ergopeptines to lysergic acid and reduction of lysergic acid) will benefit pharmaceutical industries. DHLA is not listed as a controlled substance by the US Drug Enforcement Agency (DEA) and would not be readily useful for illegal drug biosynthesis.

#### Alternate plans (DHLA):

In certain embodiments of the invention, *easA* from the DHLA producer *C. africana* along with *cloA* from *E. sp. Lp1* and *C. africana* are used. These dual-gene expression constructs

can be set up with the two genes divergently transcribed from the *A. fumigatus easA/easG* promoter, as we have done successfully with *easA* and *cloA* from *E. sp. Lp1* (Fig. 8).

#### The biosynthetic origin and engineering of dihydrolysergol (DHlysergol)(prophetic):

The maize ergot fungus produces dihydrolysergol as the end product of its ergot alkaloid pathway. Dihydrolysergol also occurs in the biosynthetic pathway to DHLA and DHLA derivatives in *C. africana* (Barrow et al., 1974). The reason that *C. gigantea* stops its pathway at DHlysergol is unknown but will be revealed by expression studies and *eas* cluster sequence analysis.

#### Testing DHlysergol:

In certain embodiments of the invention, the coding sequences of *cloA* is amplified from the initiation codon through the termination codon, along with about 300 bp of 3'UTR. Primers can be designed based on *C. gigantea* genomic sequence. In further embodiments of the invention, the *cloA* fragment is joined to the *easA* promoter of *A. fumigatus* and introduced into *A. fumigatus easM* ko by cotransformation with pBCphleo (while selecting on phlemomycin). Transformants can be analyzed by fluorescence HPLC and LC/MS as described previously.

#### Translational implications (DHlysergol):

DHlysergol would be an excellent starting molecule for several of the more important pharmaceutical ergot alkaloids, such as nicergoline, cabergoline, and pergolide (Table 3). As the end product of the engineered strain, dihydrolysergol would not need to be hydrolyzed and purified from more complex ergot alkaloids or reduced to the dihydro state. DHlysergol would not be regulated as a controlled substance, simplifying business practices and would not be easily exploited for illicit drug synthesis.

#### Alternate plans (DHlysergol):

In other embodiments of the invention, *C. gigantea cloA* is expressed in conjunction with *C. gigantea easA*.

OUTCOMES:

The present invention has a strong basic rationale founded in the historical and medicinal importance of the ergot alkaloids and novel and interesting enzymatic activities. Those persons skilled in the art will understand that the present invention has strong translational possibilities as set forth herein.

Generally, the present invention provides a strain of a fungus for expressing one or more genes of the ergot alkaloid biosynthesis pathways from one or more fungus. The fungus may be for example, but not limited to, *Aspergillus fumigatus*, *Penicillium commune*, or any fungus having a pathway similar to *Aspergillus fumigatus*, as the host fungus for gene expression.

It will be understood by those persons skilled in the art that the present invention includes using *easA* or *cloA* genes from ergot alkaloid producing fungi that are functionally similar to the genes, for example but not limited to, from *Claviceps purpurea* or any of *Epichloe* species.

Generally, the present invention provides producing novel ergot alkaloids in *A. fumigatus* by the following method: expressing ergot alkaloid synthesis genes from other fungi in *A. fumigatus easA* knockout or *easM* knockout and letting the native prenyl transferase EasL act on any ergot alkaloids so produced in order to produce novel prenylated alkaloids. This method of this invention produces novel alkaloids by expressing ergot alkaloid pathway genes from other sources.

Preferred embodiments of the present invention provide:

1. A strain of fungus comprising *Aspergillus fumigatus* (*A. fumigatus*) and expressing one or more genes of the ergot alkaloid biosynthesis pathways from one or more fungus selected from the group consisting of:
  - a. *Epichloë festucae* var. *lolii* x *Epichloë typhina* isolate Lp1 (*E. sp.* Lp1);
  - b. *Claviceps* species;
  - c. *Claviceps africana* (*C. africana*);
  - d. *Claviceps gigantea* (*C. gigantea*);
  - e. *Periglandula* species; and
  - f. *Epichloë coenophiala*,wherein gene *easA* or gene *easM* is inactivated in said *A. fumigatus*.
2. The strain of embodiment 1 above, wherein said one or more genes of the ergot alkaloid biosynthesis are selected from the group consisting of:

- a. *easA*; and
- b. *cloA*.
3. The strain of embodiment 2 above, wherein said gene *easA* is inactivated in said *A. fumigatus*, and said one or more fungus is *E. sp. Lp1*.
4. The strain of embodiment 2 above, wherein said gene *easA* is inactivated in said *A. fumigatus*, and said one or more fungus is a *Periglandula* species or *Epichloë coenophiala* that produces lysergol.
5. The strain of embodiment 2 above, wherein said gene *easA* is inactivated in said *A. fumigatus*, and said one or more fungi are a *Periglandula* species or *Epichloë coenophiala* and *E. sp. Lp1*, wherein said expressing gene *easA* is from a *Periglandula* species or *Epichloë coenophiala* and said expressing gene *cloA* is from *E. sp. Lp1*.
6. The strain of embodiment 2 above, wherein said gene *easA* is inactivated in said *A. fumigatus*, and said one or more fungi are a *Periglandula* species or *Epichloë coenophiala* and *E. sp. Lp1*, wherein said expressing gene *cloA* is from a *Periglandula* species or *Epichloë coenophiala* and said expressing gene *easA* is from *E. sp. Lp1*.
7. The strain of embodiment 2 above, wherein said gene *easM* is inactivated in *A. fumigatus*, said one or more fungus is *E. sp. Lp1*, and said expressing one or more genes of the ergot alkaloid biosynthesis is *cloA*.
8. The strain of embodiment 2 above, wherein said gene *easM* is inactivated in *A. fumigatus*, said one or more fungus is *C. africana*, and said expressing one or more genes of the ergot alkaloid biosynthesis is *cloA*.
9. The strain of embodiment 2 above, wherein said gene *easM* is inactivated in said *A. fumigatus*, said one or more fungus is *C. gigantea*, and said expressing one or more genes of the ergot alkaloid biosynthesis is *cloA*.
10. A method for producing lysergic acid comprising inactivating an ergot alkaloid biosynthesis pathway gene from the fungus *A. fumigatus* and expressing genes *easA* and *cloA* from the fungus *E. sp. Lp1*, wherein said inactivated ergot alkaloid biosynthesis pathway gene is *easA* of *A. fumigatus*.
11. A method for producing novel ergot alkaloids comprising inactivating an ergot alkaloid biosynthesis pathway gene from the fungus *A. fumigatus* and expressing genes *easA* and *cloA*

- from the fungus *E. sp. Lp1*, wherein said inactivated ergot alkaloid biosynthesis pathway gene is *easA* of *A. fumigatus*.
12. A method for producing dihydrolysergic acid (DHLA) comprising inactivating gene *easM* in *A. fumigatus* and expressing gene *cloA* from *E. sp. Lp1* or gene *cloA* from *C. africana* in said *A. fumigatus* strain.
  13. A method for producing dihydrolysergol (DHlysergol) comprising inactivating gene *easM* in *A. fumigatus* and expressing one or more genes of the ergot alkaloid biosynthesis from *C. gigantea* selected from the group consisting of:
    - a. *cloA*; and
    - b. *cloA* and *easA*,wherein said gene(s) from *C. gigantea* are expressed in said *A. fumigatus* strain.
  14. A strain of fungus comprising a species of a fungus and expressing one or more genes of the ergot alkaloid biosynthesis pathways from one or more of said fungus, wherein said fungus has a pathway similar to *A. fumigatus*.
  15. The strain of embodiment 14 set forth above, wherein said one or more genes of the ergot alkaloid biosynthesis are selected from the group consisting of:
    - a. *easA*; and
    - b. *cloA*.
  16. The strain of embodiment 15 set forth above wherein said *easA* or *cloA* genes from said ergot alkaloid producing fungi are functionally similar to the genes from *Claviceps purpurea* or any of *Epichloe* species.
  17. A method of producing ergot alkaloids in *A. fumigatus* comprising expressing ergot alkaloid synthesis genes from other fungi in *A. fumigatus easA* knockout or *easM* knockout, allowing native prenyl transferase EasL act on any ergot alkaloids so produced for producing prenylated alkaloids.
  18. A method of producing ergot alkaloids in a strain of *A. fumigatus* comprising expressing a bidirectional *easA/easG* promoter of *A. fumigatus* to drive expression of oxidase genes in the *A. fumigatus EasA* knock-out background for producing ergot alkaloids.
  19. The method of embodiment 18 set forth above, wherein a *EasA* gene from *E. sp. Lp1* is expressed in said *A. fumigatus EasA* knock-out background.

20. The method of embodiment 19 set forth above, wherein said EasA gene from *E. sp. Lp1* includes expression of *cloA*.
21. A method for the production of lysergic acid comprising providing for the expression of EasA/CloA in *A. fumigatus* easA knockout for producing lysergic acid.
22. A method of producing a festuclavine-accumulating strain of *A. fumigatus* comprising a knock-out of the easM allele for producing a festuclavine accumulating strain of *A. fumigatus*.
23. A method for producing lysergic acid in *A. fumigatus* easA knock-out providing amplifying *E. sp. Lp1* easA and *E. sp. Lp1* cloA for producing lysergic acid.
24. A method for accumulating lysergol comprising amplifying easA and cloA from *Periglandula* in plant material selected from the group consisting of *Stictocardia tiliifolia*, *S. beraviensis*, *Argyreia*, and *Ipomoea* species or by amplifying easA and cloA from *Epichloë coenophiala* for accumulating lysergol.
25. A method for producing lysergol comprising providing expressing *Periglandula sp.* easA and *P. sp.* cloA or *Epichloë coenophiala* easA and *Epichloë coenophiala* cloA in a *A. fumigatus* easA knock-out strain for producing lysergol.
26. A method for producing lysergol comprising expressing *P. sp.* easA or *Epichloë coenophiala* easA and *Epichloë sp. Lp1* cloA in a *A. fumigatus* easA knock-out strain for producing lysergol.
27. A method for producing lysergol comprising *A. fumigatus* easA knock-out strain through expression of *E. sp. Lp1* easA and *P. sp.* cloA or *Epichloë coenophiala* cloA for producing lysergol.
28. The method according to embodiments 25, 26, and 27, set forth above, including amplifying said easA and cloA based on degenerate primers designed to anneal to versions of each gene.
29. A method for producing dihydrolysergic acid comprising expressing *C. africana* cloA under the control of a *A. fumigatus* easA promoter in *A. fumigatus* easM knock-out strain for producing dihydrolysergic acid.
30. A method for producing dihydrolysergic acid comprising expressing *C. africana* easA, *C. africana* cloA, and *E. sp. Lp1* cloA using a *A. fumigatus* easA/easG promoter for producing dihydrolysergic acid.
31. A method for producing dihydrolysergol comprising expressing *C. gigantea* cloA in *A. fumigatus* easM knock-out for producing dihydrolysergol.

32. The method of embodiment 31 set forth above, including joining said cloA to a easA promoter of *A. fumigatus* to form a cloA construct and introducing said cloA construct into *A. fumigatus* easM knock-out utilizing cotransformation with pBCphleo.

33. The method of embodiment 32 set forth above, including adding a *C. gigantea* easA expressed from a *A. fumigatus* easA promoter to said cotransformation of the *A. fumigatus* easM knockout.

34. A strain of fungus comprising SEQ ID NO:4.

35. A strain of fungus comprising SEQ ID NO:7.

#### Production of lysergic acid by genetic modification of an industrially relevant fungus

The following pages set forth the following:

*Aspergillus fumigatus* easA; *Epichloë festucae* var. *lolii* × *Epichloë typhina* isolate Lp1 easA; *Epichloë festucae* var. *lolii* × *Epichloë typhina* isolate Lp1 cloA; *Aspergillus fumigatus* ergot alkaloid pathway;

Dual-gene transformation construct to express easA and cloA from *Epichloë festucae* var. *lolii* × *Epichloë typhina* isolate Lp1 in *Aspergillus fumigatus*; Recipient strain *Aspergillus fumigatus* easA knockout description; and Details of disarmed strain of *Aspergillus fumigatus*.

*Aspergillus fumigatus easA*Nucleotide sequence (coding sequence, which for this gene naturally lacks introns)

ATGCGAGAAGAACCGTCCTCTGCTCAGCTATTCAAGCCGCTCAAGGTGGGAAGATGTCATCTCCAACATAGGATGAT  
 CATGGCGCCGACAACCTCGATTCCGGGCCGATGGACAGGGGGTCCCCTTCCCTTTTGTACAAGAGTATTACGGTCAGC  
 GTGCATCGGTTCCCTGGCACCCCTCCTCATCACC GAAGCAACAGACATCACCCCAAGGCGATGGGTTACAAACATGTC  
 CCGGGGATATGGAGTGAGCCGAGCGCGAGGCGTGGAGAGAGATTGTTTCTAGAGTCCATTGAAAAAATGCTTTAT  
 TTTCTGCCAGTTATGGGCGACCGGCCGCGCCGAGATCCGGACGTACTCGCCGACATGAAGGACCTGATCTCTAGTA  
 GCGCCGTGCCTGTAGAAGAGAAGGGACCTCTTCCCCGAGCTCTGACTGAGGACGAAATCCAGCAGTGCATCGCAGAT  
 TTTGCGCAGGCGGCCGAAACGCCATCAATGCTGGGTTTCGATGGGGTGGAGATCCATGGTGCCAATGGGTACCTCAT  
 CGACCAGTTCACACAGAAGTCTTGCAACCACCGCCAGGATCGATGGGGCGGAAGCATCGAGAATCGAGCTCGTTTTG  
 CGGTGCGAGGTAACACGGGCGGTTATCGAGGCCGTTGGGTGCCGATCGTGTGCGCGTCAAACCTCTCCCCCTACAGTCAG  
 TATCTGGGGATGGGAACAATGGACGAGCTTGTGCCACAGTTTGAGTATCTCATTGCCAGATGCGGCGATTGGATGT  
 CGCATATCTCCATCTTGCCAACCTCCCGATGGCTTGATGAGGAAAAGCCCCATCCTGACCCTAATCATGAGGTGTTTG  
 TCGGTGTCTGGGGTCAATCCTCACCTATCCTGCTGGCAGGCGGGTATGATGCGGCATCGGCAGAGAAGGTGACGGAG  
 CAGATGGCGGCAGCGACTTACACCAATGTGGCCATTGCTTTTGGGAGGTACTTTATCTCGACTCCAGACCTGCCCTT  
 TCGGGTATGGCTGGCATCCAGCTTCAAAGTACGATCGTGCTCTTTCTATAGCACGCTATCAAGAGAAGGCTACC  
 TTGATTACCCTTTCAGCGCTGAATATATGGCATTGCATAATTTCCCCGTCTAA

GenBank: XM\_751040.1

Amino acid sequence (deduced from above)

MREEPSAQLFKPLKVGRCMLQHRMIMAPTTRFRADGQGVPLPFVQEEYQQRASVPGTLLITEATDITPKAMGYKHV  
 PGIWSEPQREAWREIVSRVHKKCFIFCQLWATGRAADPDVLDADMKDLISSAVPVEEKGPLPRALTEDEIQQC IAD  
 FAQAARNAINAGFDGVEIHGANGYLIDQFTQKSCNHRQDRWGGSIENRARFAVEVTRAVIEAVGADRVGVKLSYSPQ  
 YLGMGTMDLVPQFEYLI AQMRRLDVAYLHLANSRWLDEEKPHDPNHEVFVRVWQSSPILLAGGYDAASA EKVTE  
 QMAAATYTNVAIAFGRYFISTPDLFPRVMAGIQLQKYDRASFYSTLSREGYLDYPFSAEYMALHNFV

*Epichloë festucae var. lolii × Epichloë typhina isolate Lp1 easA*Note on the name of the fungus

Genes *easA* and *cloA* were cloned from the fungus “*Epichloë festucae var. lolii × Epichloë typhina isolate Lp1*”. This is one name for a single fungus with a hybrid origin; thus, the apparent multiple names within a long name. In the original disclosure, the fungus was called *Neotyphodium lolii × Epichloë typhina isolate Lp1*. After we submitted that disclosure, the fungus was renamed *Epichloë festucae var. lolii × Epichloë typhina isolate Lp1*.

Nucleotide sequence (coding sequence, which for this gene naturally lacks introns)

ATGTCAACTTCAAATCTTTTACGCGCTCCAATTTGGAAAATGTCTCCTCCAGCACAAAGCTAGTCTCTCACCGAT  
 GACTCGTTTTCTGTCGGATAATGAAGGCGTCCCCTTCCCTATGTCAAGACTTACTACTGTCAACGAGCATCTCTCC  
 CTGGCACCCCTGCTTCTTACCGAAGCTACTGCCATCTCTCGCCGAGCCAGAGGGTTTCCCAATGTCCCCGGGATTTGG  
 AGTCAGGAGCAAATTCAGGCTGGAAAGAGGTAGTTGATGCTGTGCATGCGAAGGGGTCTTATATCTGGCTGCAGCT  
 TTGGGCGACTGGACGAGCAGCCGAGGTTGGTGTCTGAAAGCGAATGGATTTGATCTCGTATCCAGCAGTCCCGTTC  
 CAGTCTCCCCGGTGAGCCACACCCCGGCGCTCAGCGACGATGAGATCAACTCATACTCGGTGATTTTCGTTCAA  
 GCAGCCAAAAATGCAGTCTTAGAAGCAGGATTTGACGGAGTCAACTCCACGGTGCCAATGGATTTCTCATCGATCA  
 GTTTCTCCAATCTCTTGCAACCAACGTACCGATCAATGGGGCGGTTGCATTGAGAATCGCTCACGGTTCGGTCTTG  
 AAATACCCGGCGAGTCATCGACGCTGTGCGTAAAGACCATGTGGGCATGAAGCTTTTCACTTGGAGTACCTTCCAG  
 GGAATGGGCACCATGGACGACCTCATACTCAGTTCGAGCATTTTCATCATGCGCCTTCGTGAGATAGGCATTGCCTA

TCTACACCTTGCTAACTCTCGCTGGGTAGAGGAGGAAGACCCCACCATCAGAACACATCCAGATATTCATAATGAGA  
CTTTTGTGCGCATGTGGGGGAAAGAGAAGCCTGTCTTTTTGGCTGGTGGCTACGGCCCGGAGTCCGCCAAGCTTGTG  
GTAGATGAAACATACTCTGACCACAAGAACATCGGTGTCTTTTTGGACGACACTATATATCCAACCCAGATCTTCC  
ATTCCGGCTGAAAATGGGACTCCCTCTTCAAAGTACAATCGGGAAACTTTCTACATTCCGTTCTCTGACGAGGGAT  
ACTTGGATTACCCCTATAGTGAGGAATACATAACAGAGAACAAGAAGCAGGCAGTTCTAGCATAA

GenBank: KC989613.1

Amino acid sequence (deduced from above)

MSTSNLFTPLQFGKLLQHKLVLSPMTRFRADNEGVLPLVYKTYQCQRASLPGTLLLLTEATAISRRARGFPNVPGIW  
SQEQIAGWKEVVDVAVHAKGSYIWLQLWATGRAAEVGVLKANGFDLVSSAVPVSPGEPTPRALSDDEINSYIGDFVQ  
AAKNAVLEAGFDGVELHGANGFLIDQFLQSPCNQRDQWGGCIENRSRFGLEITRRVIDAVGKDHVGMKLSWSTFQ  
GMGTMDLLIPQFEHFIMRLREIGIAYLHLANSRWVEEEDPTIRTHPDIHNETFVRMWGKEKPVLLAGGYGPESAKLV  
VDEYSDHKNIGVVFGRHYISNPDLFPRLKMGLPLQKYNRETFYIPFSDEGYLDYPYSEEYITENKKQAVLA

*Epichloë festucae var. lolii* × *Epichloë typhina* isolate Lp1 cloA

Nucleotide sequence (coding sequence with introns)

ATGATATTACCATGGTTATCCCAGCTTCAATCGGTCTCACTAGGGACGATTTTCTCACGCTATTCTCGTTATATT  
GACTCCTTTGGTTTTTACAAGCGTTTACCGTCTGTATTTTCATCCTCTTCGCAAAATTCTGGACCACGAACCGGGG  
GTTTGACAAGTTTCTATGGGTTCTATTGGAACGGATACGAGATGAAGGATACTCTAAGCTCTTCAATCCCCTGCAT  
AAACAATATAGTAAGGTTTATTTCCCGAATAAATACCCCTTGTGAATGCTAAGATGCATCAAGATTTCCATATCATA  
CGTATCGGCCCAAACCATGTTACATCAACCAACCGCAAGCTTTTGTAGTTCGTACAAGACTCCTCTACACTTCT  
AAACTGTGGAGGGCTCACACAAAATAAAAATAGGATATTTCAAAGTTGGAACAACATGGCGCAAAGACAGCTCATTT  
ACAAGTATTTTAAACGGCTTGGACGCCATGATTGAGCCGACGCAATATCGCACCTACCGAACTCACTTGGCCCTTTA  
TACGCACAACGCTCCATTGATGGCTTAAACACCAAAGCTCCATGACGACCTCGTGGTAACTGCCGAAAGGATGGCCAA  
GAGCATCGAAAATGGTGAACCTGTGAACATGGTGAAGATATTGCGGACATTGAGTGTAAGTATATAGTGGTTGTTCA  
AAAACCACTGTATTTGACTAACGGCCAACGGGAATAGACCTCAATGATGCTTTATACTTTGTATTTCGACGAGCATC  
CCGCTCTCTCAATATGATGGGTATCACCCGTTTCTAGAAGCTTTTGTAGCTGCTCATGACCCAAAGTTGGCTAAGTGA  
GTCTGTATCACATTTAGGTCACAGTTTGCTTTATTGTATACAGGAACGCTGATAATTTGTTTCTGTACAAAGTGAT  
CAATTATCCCATGATGGGTATGATCCTTGGCCTAATTTCCCGGCACGAGCTTTGCGAAATTCAATGCCGCTTTCGGAA  
CCTTCTTGAAGTTAGTTAACTTGCAGGAGTAACAAGGGACAAAGCACACAAATTGCTAAAAGAATGTTAATTTACAG  
TACTGTAAAGAGTGAACGACGAGGATGAACGCATTCAAAGCTTGAACCTGCTGAATCACTGCGGGACTCCCACAT  
GAAACGATACCTTGCCATTGACCCAAATAACGAGATCAAAAAGAAGGTCGTGCCGCATCCCCTGGAGGATATATTTA  
ACTTTATCGCAGGCGGTAGTGACACTACTTCATATACAGCTGCATGTGCATTCTTCCATGTTCTCTCGTCTGCTGAG  
GTGCACTCTAAGCTCGTGGCGGAGCTCGATCAAGCTTCTTTCAGTGATCAGGGATACCTTTGATTACAATAAGATTCA  
AACTTGCCATATCTGGTGTGTATACGATTAAGAGTTTACCTATCATATTTTTCCCGGACCCCTTCTGAAAAGTAG  
GCTCTAACCATGGATGTTGCAGAATGCCGTGATCAAGGAGACGCTTCGTATCTCTTGTCCGGTACCAGGGTGTCTTC  
CCCGAGTCGTCCCTGAGGGGGGAATGAATCTGGGTTTTCAGTAAATCTTCCAGCCGGTGAAGCTCCATTTATAACAAC  
TTGTATAAGACTAGTGACTTGCTAACGTTGTGATATGCGAACAGACAGTGGTGTCAATCTCCAGCTAGCCATCCAC  
TTAATGAGACGATTTTCTCGTCACCTGACAAGTTTCATCCCCGAAAGATGGCTTGGGGACGATAGAAAATCGATTGA  
GAAGTGAATATCGCTTTTTCGTCACCTGACAGTTTCATCCCCGAAAGATGGCTTGGGGACGATAGAAAATCGATTGA  
GTGATAGTATCAAAAATACCACCTTCTCTGCTATTGTAGATGAATGAATGCTGAGTTTTAACGTTTTTGTTCATA  
GTCTCGCTTATATGGAACCTACGCTGCGTCTCGCTTATTTCTTCTCCCGCTTTGAATTTAAGTTAACGGGTAGCTGT  
GGAGATAAGTTGCGCTGGGTTGATCGATTTGTCTCAGTCAACTTGGACGATGTGAGGTCATCTGTAAGGACCG  
ATGGGCGTAA

GenBank: KC989583.1

Amino acid sequence (deduced from above)

MILPWLSQLQSVSLGTIFLTLFLVILTPLVFTSVYRLYFHPLRKIPGPRTGGLTSFYGFYWNWIRDEGYSKLFNPLH  
 KQYNISHIIRIGPNHVHINQPQAFDEIFKVGTTWRKDS SFYKYFNGLDAMIEPTQYRTYRTHLAPLYAQRSIDGLTPK  
 LHDDLVTVAERMAKSIENGEVPMVMVKILRLTLSTSMMLYTLYSQDIPLSQYDGYHPFLEAFELLMTQSWLMINYPMMG  
 MILGLIPGTSFAKFNAAFGTFLKYCKEWNDEDERIQKLETAESLRD SHMKRYLAIDPNNEIKKKVVPHPLEDIFNFI  
 AGGSDTTSYTAACAFFHVLSSSEVHSKLVAELDQASSVIRDTFDYNKIQNLPLYLNAVIKETLRI SCPVPGCLPRVVP  
 EGGMNLG SVNLPAGTVVVISQLAIHFNETIFSSPKDFIPERWLGDDRKSI EKWNIAF SRGPRQCIGTTLAYMELRCV  
 LAYFFSRFEFKLTGSCGDKLRWVDRFVSVNLDDVEVTIVKDRWA

The *Aspergillus fumigatus* ergot alkaloid pathway is set forth in Figure 14. Ergot alkaloid pathway of *Aspergillus fumigatus*. Roles for genes are indicated between intermediates or products. Double arrow indicates one or more uncharacterized intermediates: DMAPP, dimethylallylpyrophosphate; DMAT, dimethylallyltryptophan; Trp, tryptophan.

Figure 8 shows Dual-gene transformation construct (construct corresponding to SEQ ID NO:4) to express *easA* and *cloA* from *Epichloë festucae* var. *lolii* × *Epichloë typhina* isolate Lp1 in *Aspergillus fumigatus*. The coding sequences and 3' untranslated sequences from *easA* and *cloA* were joined divergently and at alternate ends of the bidirectional *easA/easG* promoter from *Aspergillus fumigatus* (GenBank: NC\_007195.1). The construct was prepared by fusion PCR, and the sequence of the completed construct is provided below (in a manner that corresponds to the diagram set forth in Figure 8). The first shaded portion corresponds to the reverse complement of the *Epichloë festucae* var. *lolii* × *Epichloë typhina* isolate Lp1 *easA* sequence (including 264 bp of 3' untranslated sequence), the central, unshaded portion is the *Aspergillus fumigatus* promoter, and the second shaded portion is the *Epichloë festucae* var. *lolii* × *Epichloë typhina* isolate Lp1 *cloA* sequences (including 634 bp of 3' untranslated sequence).

CGTATCACCGAGACAAAGAGGGCGCATCATTCACTATCAATTATTTTCAGAGATATCTAAATGAAACAAAATGACTAC  
 AGTATTGTATAATGATCACGGAGCACCAAAGACTAAGAAGACAATGATAAAGATAACTTAATGAACGAAATACAAAA  
 GCCATACCACACTAGTGTACCTATTCGGTATAAGATTTAACTCTTAGAGGAATCATTTATAAGGCTAATCCAAAAAG  
 ATGCAAAAGCATTGCC TGGACTGCGATAATGATTTATGCTAGA ACTGCCTGCTTCTTGTTCTCTGTTATGATTCCT  
 CACTATAGGGGTAATCCAAGTATCCCTCGTCAGAGAACGGAATGTAGAAAGTTTCCCGATTGTACTTTTGAAGAGGG  
 AGTCCCATTTTCAGCCGGAATGGAAGATCTGGGTGGATATATAGTGTCTCGTCCAAAAACGACACCCGATGTTCTTGTG  
 GTCAGAGTATGTTTCATCTACCACAAGCTTGGCGGACTCCGGGCGGTAGCCACCAGCCAAAAGGACAGGCTTCTCTT  
 TCCCCACATGCGCACAAAAGTCTCATTATGAATATCTGGATGTGTTCTGATGGTGGGGTCTTCCCTCTTACCCAG  
 CGAGAGTTAGCAAGGTGTAGATAGGCAATGCCTATCTCACGAAGGCGCATGATGAAATGCTCGAACTGAGGTATGAG  
 GTCGTCCATGGTGGCCATTCCCTGGAAGGTACTCCAAGTGGAAAGCTTCATGCCACATGGTCTTTACCGACAGCGT  
 CGATGACTCGCCGGGTGATTTCAAGACCGAACCCTGAGCGATTCATCAATGCAACCGCCCCATTGATCGGTACGTTGG  
 TTGCAAGGAGATTGGAGAACTGATCGATGAGAAATCCATTGGCACCGTGGAGTTCGACTCCGTCAAATCCTTGCTTC  
 TAGGACTGCATTTTGGCTGCTTGAACGAAATCACCGATGTATGAGTTGATCTCATCGTTCGCTGAGCGCCCCGGGGTG  
 TGGGCTCACCGGGGAGACTGGAACGGCAC TGTGGATACGAGATCAAATCCATTTCGCTTTCAGAACACCAACCTCG  
 GCTGCTCGTCCAGTCGCCCAAAGCTGCAGCCAGATATAAGACCCCTTCGCATGCACAGCATCAACTACCTCTTTCCA  
 GCCTGCAATTTGCTCCTGACTCCAAATCCCGGGGACATTGGGAAACCCCTCTGGCTCGGCGAGAGATGGCAGTAGCTT

CGGTAAGAAGCAGGGTGCCAGGGAGAGATGCTCGTTGACAGTAGTAAGTCTTGACATAGGGAAGCGGGACGCCTTCA  
TTATCCGCACGAAAACGAGTCATCGGTGAGAGGACTAGCTTGTGCTGGAGGAGACATTTTCCAAATTGGAGCGGCGT  
GAAAAGATTTGAAGTTGACATTGCTTCTAATCCACCAAGTACTTGAACACGGTGAATGTGGAAGCTCAGTCTGACC  
AGTGGAGGTATCGACGCGAACTTTTTAGGTCATGGAAGTGTGGAGTATGGTCTACAGGCTTGGAGGACTTTGTATTG  
ATTCCTGGCATCGATAACTGAGCAGACAAGACGCCATTCGGGCACAATTTCTTTCTGCTGGACAATTCATACAGCC  
ATGTCGTCCCCCTTGCCGAGCCAACGCCACTATTTGTTTATGTGTCTATTATTCGATATTCACGGGGAAAAGGTGAGC  
TGACTTGTACGTACTCTGTCTACTCCAATGCCCTCACCTTTCTTCAGCTGCAGAGCCGTGGAGCGGAACTCCTTGCT  
TCCCGTTTACATACTTGGGAATTGAAATCAGGACCCATATCTCCATGACGAGTCTTTTATCATGCACATGGGAAAT  
GGCGGTCAAGTAAAACATGATCAATACTACTGTTACGCCTTTACTCCAATGCACCGATAGCTAATAAGAAGAGCTCC  
TCCACCTCCCACAAAGAGGCAAGGGAGAGCCAGAAGAGACTGAGGGTGGTGGGCGAAAACAGCTCCAAGCGTATAT  
GTGCTACTGTGCCAAAGACTTCCCGTACTTTCTCAATGTGTGAATAATGAGGACTAGACGAGACACTCTTAATAAG  
AGATCATCTACCAGAAAGGGCGTACGTTACTACCAAACCTGTGTGATTAAATGTACACACATCTTTCAACAAACA  
AATTTGATCCACTTCTATAGAGTAGGCACCTCCGCACCATGATATTACCATGGTTATCCCAGCTTCAATCGGTCTCA  
CTAGGGACGATTTTCTCACGCTATTCTCGTTATATTGACTCCCTTTGGTTTTTACAAGCGTTTACCCTGTGATTT  
TCATCCCTTCGCAAAATTCTGGACCACGAACCGGGGTTTTGACAAGTTTTCTATGGGTCTATTGGAACTGGATAC  
GAGATGAAGGATACTCTAAGCTCTTCAATCCCTGCATAAAACAATATAGTAAGGTTTTATTTCCCGAATAAAATACCCC  
TTGTGAATGCTAAGATGCATCAAGATTCCCATATCATACTGATCGGCCAAAACCATGTTACATCAACCAACCGCAA  
GCTTTTGATGAGTTCGTACAAGACTCCTCTACACTTCTAAACTGTGGAGGGCTCACACAAAATAAAATTAGGATATT  
CAAAGTTGGAACAACATGGCGCAAAGACAGCTCATTTTACAAGTATTTTAACGGCTTGGACGCCATGATTGAGCCGA  
CGCAATATCGCACCTACCAGACTCCTTGGCCCTTTTATACGCACAACGCTCCATTGATGGCTTAACACCAAGCTC  
CATGACGACCTCGTGGTAACTGCCGAAAGGATGGCCAAGAGCATCGAAAATGGTGAACCTGTGAACATGGTGAAGAT  
ATTGCGGACATTGAGTGTAAAGTATATAGTGGTTGTTCAAAAACCACCTGTATTTGACTAACGGCCAACGGGAATAGA  
CCTCAATGATGCTTTATACTTTGTATTTCGAGGACATCCCGCTCTCTCAATATGATGGGTATCACCCGTTTCTAGAA  
GCTTTTGAGCTGCTCATGACCCAAAGTTGGCTAAGTGTAGTCTGTATCACATTTAGGTCACAGTTTTGCTTTATTGTA  
TACAGGAACGCTGATAATTTGTTTTCTGTACAAAGTGTATCAATTTATCCCATGATGGGTATGATCCITGGCCCTAAITCC  
CGGCACGAGCTTTGCGAAATTCATGCCGCTTTTCGGAACCTTCTTGAAGGTTAGTTAACTTGGCGGAGTAAACAAGGGA  
CAAAGCACACAAATTTGCTAAAAGAATGTTAATTTACAGTACTGTAAAGAGTGGAAACGACGAGGATGAACGCATTCAA  
AAGCTTGAAC TGCTGAATCACTGCGGGACTCCCACATGAACGATACCTTGCCATTGACCCAAATAACGAGATCAA  
AAAGAAGTCTGTCGCGCATCCCTGGAGGATATTTAACTTTATCGCAGGCGGTAGTGACCACTCATATACAG  
CTGCATGTGCATTTCCATGTTCTCTCGTCTGAGGTGCACCTAAGCTCGTGGCGGAGCTCGATCAAGCTTCT  
TCAGTATCAGGGATACCTTTGATTACAATAAGATTTCAAAACTTGCCATATCTGGTGTGTATACGATTAAGAGTTTA  
CCTATCATCATTTTTTCCCGGACCCCTCTTCTGAAAGTAGGCTCTAACCATGGATGTGTCAGAATGCCGTGATCAAGGA  
GACGCTTCGTATCTTTGTCGGGTACCAGGGTGTCTTCCCGGAGTCTGTCCTGAGGGGGGAATGAATCTGGGTTCAG  
TAAATCTTCCAGCCGGTGTAAAGCTCCATTTATACAACCTTGTATAAGACTAGTGACTTGCTAACGTTGTGATATGCG  
AACAGACAGTGGTGTCAATCTCCAGCTAGCCATCCACTTTAATGAGACGATTTTCTCGTCACCTGACAAGTTCATC  
CCCAGAAAGATGGCTTGGGGACGATAGAAAATCGATTGAGAAGTGGAAATATCGCTTTTAGCAGAGGACCTCGACAGTG  
CATTGGGACAACGTAAGTCTTCCCCCCCCCGATCCGGTGTATAGTATCAAAATACCACCATTCTCTGCTATTGTAG  
ATGAATGAATGCTGAGTTTTAACGTTTTTTGTTCCATAGTCTCGCTTATATGGAAC TACGCTGCGTCCCTCGCTTATT  
TCTTCTCCCGCTTTGAATTTAAGTTAACGGGTAGCTGTGGAGATAAGTTGCGCTGGGTTGATCGATTTGTCTCAGTC  
AAC TTGGACGATGTCGAGGTCACTATCGTGAAGGACCGATGGGCGTAAGCTGAAAAGCGTCCAAAAGTGCCCGGGAGG  
CGTAGGCACGGCCAGAGGGATGTATCTTGACTTGGAGAAAATTAAGGGCGGGGAAGCAAGTTAAACTAGGATCTTTCC  
ATAGTACTATTTAATGAGCTAACCCTATGAAGTGTGAGGGGACAAGGGTATTAACGAGTTCAAATGCCGCTTACATA  
TAGCGATTTTTCACGAGAGACAGAGATTCTAAATGCCTTAGTTATATTAAGTAAC TAAAAACTGTAAC TTAAGCCT  
CGCTAGTAATGTCACAATATTTATAAAGTGTAGACATTTATCAAAATATAAAGCCACATCGTCTTTTACGTGGAGCA  
CATTTTAGGAGACATAGGGAAGGTATAAGAGGGAACTGTACAGTATTCTCAGACTTTATAATAATAACAGTCA  
ATGTTAGAGAAAATATATGGTTCTTTGAGATTTGTAAACACAGAGCCATTAAAGACGTTGTTTAGGCAATGTCTTAAT  
AGTGGTGAAGTACC CGGTAGTAATGTGCATGATTTTAAATTAGCCATAGCAGGCATACGTGCCTTTAGTTAGTACT  
TATGCTTATTGCTTACC TAAATACACGCCATACCTAACGTTTATCGCTTGTGCCCCCTTAGCGTGT

Recipient strain *Aspergillus fumigatus easA* knockout description:

The *Aspergillus fumigatus easA* knockout mutant was prepared previously. The properties of the mutant are described in detail in the following publication: Coyle, C.M., Cheng, J.Z., O'Connor, S.E., Panaccione, D.G. 2010. An old yellow enzyme gene controls the branch point between *Aspergillus fumigatus* and *Claviceps purpurea* ergot alkaloid pathways. *Applied and Environmental Microbiology* 76:3898-3903.

Briefly, the coding sequence of *Aspergillus fumigatus easA* (unshaded below) was disrupted after nucleotide 777 of the 1131-nt coding sequence by insertion of a plasmid, pCR2.1 (shaded below) (product of Invitrogen, Life Technologies, Grand Island, NY).

ATGCGAGAAGAACCGTCCTCTGCTCAGCTATTCAAGCCGCTCAAGGTGGGAAGATGTCATCTCCAACATAGGATGAT  
CATGGCGCCGACAACTCGATTCCGGGCCGATGGACAGGGGGTCCCCTTCCTTTTGTACAAGAGTATTACGGTCAGC  
GTGCATCGGTTCTGGCACCCTCCTCATCACCGAAGCAACAGACATCACCCCAAGGCGATGGGTTACAAAACATGTC  
CCGGGGATATGGAGTGAGCCGAGCGCGAGGCGTGGAGAGAGATTGTTTCTAGAGTCCATTGAAAAAATGCTTTAT  
TTTCTGCCAGTTATGGGCGACCGGCCGCGCCGAGATCCGGACGTACTCGCCGACATGAAGGACCTGATCTCTAGTA  
GCGCCGTGCCTGTAGAAGAGAAGGGACCTCTTCCCCGAGCTCTGACTGAGGACGAAATCCAGCAGTGCATCGCAGAT  
TTTGCGCAGGCGGCCCGAAACGCCATCAATGCTGGGTTTCGATGGGGTGGAGATCCATGGTGCCAATGGGTACCTCAT  
CGACCAGTTCACACAGAAGTCTTGCAACCACCGCCAGGATCGATGGGGCGGAAGCATCGAGAATCGAGCTCGTTTTG  
CGGTCGAGGTAACACGGGCGGTTATCGAGGCCGTGGGTGCCGATCGTGTCCGGCGTCAAACCTCTCCCCCTACAGTCAG  
TATCTGGGGATGGGAACAATGGACGAGCTTGTGCCACAGTTTGAGTATCTCATTGCCAGATGCGGCGATTGGATGT  
CGCATATAGCGCCCAATACGCAAACCGCCTCTCCCCGCGCGTTGGCCGATTTCATTAATGCAGCTGGCAGCAGAGGTT  
TCCCGACTGGAAAGCGGGCAGTGAGCGCAACGCAATTAATGTGAGTTAGCTCACTCAITAGGCACCCAGGCTTITAC  
ACTTTATGCTTCCGGCTCGTATGTTGTGTGGAATTTGTGAGCGGATAACAATTTACACAGGAAACAGCTATGACCAI  
GATTACGCCAAGCTTGGTACCGAGCTCGGATCCACTAGTAACGGCCGCGCAGTGTGCTGGAATTCGGCTTAAGCCGAA  
TTCGTCAGATATCCATCACACTGGCGGCCGCTCGAGCATGCATCTAGAGGGCCCAATTCGCCCTATAGTGAGTCGTA  
TTACAATTCACATGGCCGTCGTTTTACAACGTCGTGACTGGGAAAACCCCTGGCGTTACCCAACCTAATCGCCTTGCA  
CACATCCCCCTTTCGCCAGCTGGCGTAATAGCGAAGAGGCCCGCACCCGATCGCCCTCCCAACAGCTTGGCGAGCCTG  
AATGGCGAATGGGACGCGCCCTGTAGCGGGCGCATTAAAGCGCGGGGTTGGTGGTTACGCGCAGCGTGACCCGCTAG  
ACTTGCCAGCGCCCTAGCGCCCGCTCCTTTTCGCTTTCTTCCCTTCCTTTCTCGCCACGTTTCGCCGGCTTTCGCCGTC  
AAGCTCTAAATCGGGGGCTCCCTTTAGGGTTCCGATTTAGAGCTTTACGGCACCTCGACCGCAAAAAAAGCTTGATTTG  
GGTGATGGTTACGTAAGTGGGCCATCGCCCTGATAGACGGTTTTTCGCCCTTTGACGTTGGAGTCCACGTTCTTTAA  
TAGTGGACTCTTGTTCCAAACCTGGAACAACACTCAACCCTATCGCGGTCTATTCTTTTGATTTATAAGGGATTTTGC  
CGATTTCCGGCTATTGGTTAAAAAATGAGCTGATTTAACAATTCAGGGCGCAAGGGCTGCTAAAGGAACCGGAACA  
CGTAGAAAGCCAGTCCGCAGAAACGGTGCTGACCCCGGATGAATGTCAGCTACTGGGCTATCTGGACAAGGGAAAAC  
GCAAGCGCAAAGAGAAAGCAGGTAGCTTGCAGTGGGCTTACATGGCGATAGCTAGACTGGGCGGTTTTATGGACAGC  
AAGCGAACCGGAATTGCCAGCTGGGGCGCCCTCTGGTAAGGTTGGGAAGCCCTGCAAAGTAAACTGGATGGCTTTCT  
TGCCGCCAAGGATCTGATGGCGCAGGGGATCAAGATCTGATCAAGAGACAGGATGAGGATCGTTTTCGCATGATTGAA  
CAAGATGGATTGCACGCAGGTTCTCCGGCCGCTTGGGTGGAGAGGCTATTCCGGCTATGACTGGGCACAACAGACAAT  
CGGCTGCTCTGATGCCGCCGTTTCCGGCTGTGAGCGCAGGGGGCGCCCGGTTCTTTTTGTCAAGACCCGACCTGTCCG  
GTGCCCIGAATGAACGTCAGGACGAGGCAGCGCGGCTATCGTGGCTGGCCACGACGGGCGTTCCCTTGCGCAGCTGTG  
CTCGACGTTGTACTGAAGCGGGAAGGGACTGGCTGCTATTGGGCGAAGTGCAGGGGCGAGGATCTCCTGTCTATCTCG  
CCTTGCTCCTGCCGAGAAAGTATCCATCATGGCTGATGCAATGCGGCGGCTGCATACGCTTGATCCGGCTACCTGCC  
CATTTCGACCACCAAGCGAAACATCGCATCGAGCCGAGCAGCTACTCGGATGGAAGCCGGTCTTGTGATCAGGATGAT  
CTGGACGAAGAGCATCAGGGGCTCGCGCCAGCCGAATGTTCCGCAAGGCTCAAGGCGGCATGCCCGACGGCGAGGA  
TCTCGTCTGATCCATGCGGATGCTTGTGCGCAATATCATGGTGGAAAATGGCCGCTTTCTGGATTCAACGACT  
GTGGCCGGCTGGGTGTGGCGGACCGCTATCAGGACATAGCGTTGGATACCCGTGATATTGCTGAAGAGCTTGGCGGC  
GAATGGGCTGACCGCTTCTCGTGTCTTACGGTATCGCCGCTCCCATTTCGAGCGCATCGCCCTCTATCGCCCTTCT

TGACGAGTTCCTTCTGAATTGAAAAAGGAAGAGTATGAGTATTCAACATTTCCGTGTCGCCCTTATTCCCTTTTTTGC  
GGCATTTTGCCTTCCGTGTTTTTGCCTCACCCAGAAACGCTGGTGAAGTAAAAGATGCTGAAGATCAGTTGGGTGCAC  
GAGTGGGTACATCGAACTGGATCTCAACAGCGGTAAGATCCTTGAGAGTTTTCGCCCCGAAGAACGTTTTCCAATG  
ATGAGCACTTTTAAAGTTCTGCTATGTCATACACTATTATCCCGTATTGACGCCGGGCAAGAGCAACTCGGTCGCCG  
GGCGCGGTATTCTCAGAATGACTTGGTTGAGTACTCACCAGTCACAGAAAAGCATCTTACGGATGGCATGACAGTAA  
GAGAATTATGCAGTGTCTGCCATAACCATGAGTGATAACACTGCGGCCAACTTACTTCTGACAACGATCGGAGGACCG  
AAGGAGCTAACCCTTTTTTGCACAACATGGGGGATCATGTAACTCGCCCTTGATCGTTGGGAACCGGAGCTGAATGA  
AGCCATACCAAACGACGAGAGTGACACCACGATGCCTGTAGCAATGCCAACAACGTTGCGCAAACATTAACCTGGCG  
AACTACTTACTCTAGCTTCCCGGCAACAATTAATAGACTGGATGGAGGCGGATAAAGTTGCAGGACCACCTTCTGCGC  
TCGGCCCTTCCGGCTGGCTGGTTTATTGCTGATAAATCTGGAGCCGGTGAGCGTGGGTCTCGCGGTATCATTGCAGC  
ACTGGGGCCAGATGGTAAGCCCTCCCGTATCGTAGTTATCTACACGACGGGGAGTCAGGCAACTATGGATGAACGAA  
ATAGACAGATCGTGAATAGGTGCCTCACTGATTAAGCATTGGTAAGTGTGACACCAAGTTTACTCATATATACTT  
TAGATTGATTTAAAACCTCATTTTTAATTTAAAAGGATCTAGGTGAAGATCCTTTTTGATAATCTCATGACCAAAAT  
CCCTTAACGTGAGTTTTCGTTCCTGAGCGTCAGACCCCGTAGAAAAGATCAAAGGATCTTCTTGAGATCCTTTTTF  
TTCTGCGCGTAATCTGCTGCTTGCAAAACAAAAAACACCCTGACAGCGGTGGTTTTGTTTGCCTGATCAAGAGCTA  
CCAACCTTTTTTCCGAAGGTAACCTGGCTTTCAGCAGAGCGCAGATACCAAATACTGTCTTCTAGTGTAGCCGTAGTT  
AGGCCACCACCTCAAGAATCTGTAGCACCCTACATACCTCGCTCTGCTAATCCTGTACCAGTGGCTGCTGCCA  
GTGGCGATAAGTGTCTTACCCTGGTGGACTCAAGACGATAGTTACCCTGATAAGGCGCAGCGGTGCGGCTGAACG  
GGGGTTTCGTGCACACAGCCAGCTTGGAGCGAACGACCTACACCGAACTGAGATACCTACAGCGTGAGCATTGAGA  
AAGCGCCACGCTTCCCGAAGGGGAGAAAGGCGGACAGGTATCCGGTAAGCGGCAGGGTCCGAACAGGAGAGCGCACGA  
GGGAGCTTCCAGGGGGAAACGCTTGGTATCTTTATAGTCTGTGCGGGTTTCGCCACCTCTGACTTGAGCGTCTGATTT  
TTGTGATGCTGCTCAGGGGGGGCGGAGCCTATGGAAAACGCCAGCAACGCGGCCCTTTTACGGTCTCTGGCCTTTTG  
CTGGCCTTTTGCTCACATGTTCTTTCCTGCGTTATCCCTGATTCTGTGGATAACCGTATTACCCTTTGAGTGAG  
CTGATACCGCTCGCCGACCCGAACGACCGAGCGCAGCGAGTCACTGAGCGGAGGAAGCGGAAGCTCCATCTTGCCAA  
CTCCCGATGGCTTGATGAGGAAAAGCCCATCTGACCCTAATCATGAGGTGTTTTGTGCGTGTCTGGGGTCAATCCT  
CACCTATCTGCTGGCAGGCGGGTATGATGCGGCATCGGCAGAGAAGGTGACGGAGCAGATGGCGGCAGCGACTTAC  
ACCAATGTGGCCATTGCTTTTGGGAGGTACTTTATCTCGACTCCAGACCTGCCCTTTCCGGTTCATGGCTGGCATCCA  
GCTTCAAAGTACGATCGTGCCTTTCTATAGCACGCTATCAAGAGAAGGCTACCTTGATTACCCTTTACGCGCTG  
AATATATGGCATTGCATAATTTCCCCGTCTAA

Description of disarming mutation in the *alb1* gene of *Aspergillus fumigatus*

Nucleotides 1,278 through 2,705 of the 6,662-bp coding sequence of the *alb1* gene of *Aspergillus fumigatus* (GenBank: XP\_756095.1) were deleted by homologous recombination with a construct designed as illustrated. The replacement of 1,427 bp of *alb1* sequences with any sequences would create a similar knockout mutation. Successful knockout of the *alb1* gene results in an albino fungus (whereas the wild type is dark gray-green) and a loss of virulence as experimentally demonstrated by Tsai et al. (1998). Tsai, H. F., Chang, Y. C., Washburn, R. G., Wheeler, M. H., and Kwon-Chung, K. J. 1998. The developmentally regulated *alb1* gene of *Aspergillus fumigatus*: Its role in modulation of conidial morphology and virulence. *Journal of Bacteriology* 180:3031-3038.

Nucleotide sequence of the *alb1* gene of *Aspergillus fumigatus* (required for melanin biosynthesis) SEQ ID NO:6

ATGGAGGATCTCCATCGCCTCTATCTCTTTGGAGATCAGACAATCAGCTGTGACGAAGGCTCCGCAACCTCTTGCA  
GGCGAAGAACCATACTATCGTCGCCTCGTTTCATCGAAAGATGCTTCCATGCACTGCGTCAGGAAATCACCAGGCTGC  
CGCTTCTCAGCGCACGCTCTTCCCGCGGTTTACCAGCATCGCCGACTTGCTTGCTCAGCATCGTGAGTCAGGGACA  
AACCTGCGCTGGGGAGCGCGCTGACCTGTATCTATCAACTGGGGTGTTCATCGAGTAAGTCGCCTTGCAAGGTAT  
TCTGGACTGTGGCTGATCCTGGATAGTTACCACGGTGATCGTGACATCCATATCCGTCTCGGATGACGGCTTCT  
GGGTTTCATGTACGGGTATGTTGAGTTGCACCGCAGTCAGCTCGTGCAAGAATGTGCGAGAATACTACTGCCGCTGGCAG  
TCGAGATTGTGAGATTGACTATCCACCTCGGGCTCTGTGTTCATGAGAGTCCGAGAGATGGTGGACTCGACGGAGTCA  
TCCTCCGGCAGCTGGTCAATCCTCGTCTCGGAGATCAACGAGGCAGATGCCACCAGCCTGATTGGCAATTTTGTCAA  
GAAGCGAGTAAGTACAGTGTACGACCATTGGAAGAAGAATATTGACAATACCAGGGAATCCCCCTCGTCGCAACC  
GTACATCAGCGCGGTTGGATCGAAAGGTCTCACCATCAGTGCACCACCCGAAATTTCTCGACAACCTTATCGAAGAAG  
GTCTTCCGAAGGAGTACAAACACTTCAAGGCTCCTGGAGTCACTGGTCCGTACCACGCGCCCCATCTGTACAATGAC  
CGAGAAATTCGCAATATCCTCAGCTTCTGCTCCGAGGACGTGATTCTGCGCCACACACCACGGGTTCCACTGGTCTC  
GAGCAACACAGGGAAGCTGGTCCAGGTAAGAGCATGCGTGATCTGCTAAAGGTGGCTCTGGAGGAAATCCTCTTGC  
GCAAGATCTGCTGGGACAAAGTCACCGAGTCATGCCTTTCATCGTTCAGGCTACCAACGACAAGCCCTGGAGGATT  
CTCCCTATCGCCAGCAACGCCACGCAAGGCTTGGTTACTGCACTCCAGCGTATGGGAAACTGCCAGATCGAGGTAGA  
CACCAGGGTTCGGCGCTCCTCAAATGGACCCGGCCGCTCCCAATGCAACGGGCAATGCTTACGGTCTAAGATCGCCA  
TCATCGGAATGTCTGGGCGGTTCCCTGAGGCAGATGGTATCGAGGCCTTTTGGGACTTGTGTATAAAGGTCTGGAT  
GTTACAAAAAGGTCCCACCTGAGCGATGGGATGTGGACGCGCACGTGGACTTGACCGGCACAAAGAGAAACACCAG  
CAAGGTCCATACGGTTGCTGGATCAACGAGCCCGGCTGTTTCGATGCCCGTTTCTTCAACATGTCTCCTCGGGAAG  
CACTCCAGGCAGACCTGCGCAGCGACTGGCGCTGCTGTGCGCTTACGAGGCCCTGGAATGGCAGGCTTCGTTCG  
AACAGCAGTCCATCGACTCAGAGAGACCAGCGCTCGGCATCTTCATGGGTATGACCAGCGACACTACCGTGAGATCAA  
CAGCGGTGAGGATATCGACATACTTCAATCCTGGAGGGAACCGGATTCACGCCTGGTCTGATCAACTACTACT  
TCAAGTTCAGTGGGCTAGTGTGAGTGTGACACCGCCTGCTCGTCCAGTCTTGTGCCATCCACTTGGCCTGCAAC  
GCCATCTGGAGGAATGACTGCGATAACGCCATCAGTGGTGGTGTAAACCTCCTTACTAACC CGGACAACCATGCCGG  
TCTGGATCGCGGCCACTTTCTGTCTCGGACAGGAAACTGCAACACCTTTCGACGACGGCGCGGATGGCTACTGCCGGG  
CGGACGGGGTGGGCACGATCGTCTGAAGCGCTGGAGGATGCTGAGGCTGACAACGATCCCATTTGGGAGTCATT  
AACGCGGCCCTACACCAACCACTCGGCCGAAGCCGTCTCCATTACCCGCCCTCACGTGCGCGCAGGCGTTCATCTT  
CAACAAGCTCCTCAACGACACCAACCAACCCACACGAGATTGGCTACGTGGAATGCACGGAACAGGTACTCAGG  
CGGGCGACCGGTTGAGATGCAGTCCGTCTCGACGTCTTCGCACCCGACTACCGCCGCGGGCCGGCCAATTCCTT  
TATCTGGGTTCCGCCAAATCGAACATCGGCCACGGGAATCAGCTTCCGGAGTGACATCCTTGGTCAAGGTCTGT  
GATGTTGAAGCAGAACATGATCCCGCCCACTGCGGAATCAAAACAAAGATCAATCACAACCTCCCCACGGATCTGG  
CCCAGCGCAATGTCCATATTGCCTTCAAGCAACCCCTGGAACAGACCGGTCTCGGGCAAGCGGAAGATGTTTCATC  
AACAACTTCTGTGCTGCGGGCGGCAACACCGCTCTCCTGATGGAAGATGCCCCCTGCGTGAGATCACAGGGCAGGA  
TCCCCGGAATGTGCATGTGGTGTCTGTGACGGCACGGTGCAGACTGCGCTGAAGCGTAACATCAACCGGTTGATCA  
AGTACATCAACACGCATGCGCCCTCGTTCGCGGCGAATGAGCGACGGTTCCTGGCCAGTCTGGCTTATACTACTACC  
GCGCGTGCATGCATCACCCCTTACGGTACCGCAGTGGGGTTCGAGCGTGAAGGATATCCGGGAGGTCTGCGTCA  
ACGTGCCGATCAGGATGTCACCACCCCGTCCCTGCGACAGCCCCAAGACTGGGTTTCGTCTTACCAGGTCAGGGAG  
CTCAGTACACAGGGATGGGCAAGCAATTGTACGAGGACTGTGCCACATTCAGAAGCACGATTACCCGACTCGATTGC  
ATTGCTCAAAGCCAAGGGTTCCCTCCATTCTACCCTTGTGAGGTTAGTATGCTGTGGAAGAAGTACGAGGCTGT  
CGTGACCCAGCTAGGAACCACATGCCTGCAGATGGCTCTGGTTCGACTACTGGAAGGGTCTTGGTGTCACTCCTGCGT  
TTGTTCTGGGACATAGTCTGGGAGACTACGCAGCGTTGAACAGTGCGGGCGTCTTGTCCACCAGCGATACGATTTAC  
CTCTGTGGCCGTCGCGCGCAGCTTCTCACGCAGCAGTGTGAGATGGGGACCCACGCCATGCTTGGCGTCAAGGCTGC  
CGTCTCCGAGATTCAACATCTGCTCGATCCAGACGTCCACGCCGTGCGCTGCATCAATGGACCAACCGAAACGGTCA  
TCAGCGGGCTCAGCGGTGCAATCGATGAATTGGCACAGCAGTGTCCAGCCAAAATCTCAAGTCCACCAAGCTCAAA  
GTGCCGTTTCGCTTCCACTCGGCCAAAGTGGACCCGATTCTCGAGTTCGTTTGAAGAGAGTGTCTCAGGGGGTCACTT  
CCACGAACCTGCCGTTCCGTTTCGTCTCTGCTCTGAACGGAGAGGTAATCACGGAGTGAACCTACAGCGTGTGGCC  
CCACGTATATGGTGAAGCATTGTGCGGAAGCCGTCAATTTCTTGGCGCTCTTGGAGGCGACCCGGCACGCCAAGTTG  
ATGGATGACGCCACACTCTGGGTGCAAGTGGGATCCCATCCATTTGCTCGGGTATGATCAAGTCCACCTTTGGCCC  
GCAGGCGACTACCGTTCCCTCGCTCCGCCGCGACGACGATCCATGGAAAATCCTCTCCAACAGCCTCTCCACGCTGC  
ACCTTGCAGGCGTCGAGCTCAACTGGAAGGAATTCACCAGGACTTCAGCTCGGCTCACGAGGTTCTCGAGTTACCC  
CGGTACGGCTGGGATCTGAAGAATTACTGGATCCCCTACACGAACAACCTTCTGCCTTACCAAGGGGGTCCCGTTAC  
CGCGGAGGTATCGGCGCCCAAGTCTACCTTCTCACGACCGCGGCGCAAAAGATTGTGGAATGCCGGGAGGACGGAA

ACACGGCGACATTGGTAGTTGAGAATAATATCGCAGAGCCAGAACTCAACCGTGTTATCCAAGGTCACAAGGTCAAT  
GGAGTGGCTCTTACGCCATCGGTGAGTTTGAAGTGCCTCACCCTCTGGAATAGAAAGCTAATCCCTATACGTAGT  
CTCTCTACGCTGATATTGCGCAAACGCTTGTGCGACCCTTGATCACAAAATACAAACCAGAGTACCAGGGCCTAGGT  
CTGGACGTGTGCGACATGACTGTGCCCAAGCCTCTCATAGCCAAGTCCGGAGATCAATTCTTCAGAGTCTCGGCGGT  
GATGAGCTGGGCCGAGCAGAAGGCGAGCGTGCAAGTCTGGTCTGTGAACGGAGACGGCAAGAAAATGGCCGAGCAG  
CCCATTGCCTGTCAAGCTCTTCAACTGCGCCGAGCGCGAGACGGAGTGGAAAGAGAAAATCCTACCTCATCAAACGA  
AGTGTCTCTCTCTGAGGACAAGGCGCAGACCAGGCGAGGCTCACCAGCATGCAGCGAGGAATGGTGTACAAGCTGTT  
TGCTGCTCTGGTGGACTATGACGAAAATTTCAAGGCCATCCAGGAAGTCATCCTGGACAGCAATGAGCATGAAGCCA  
CGGCGCGAGTCAAGTTCCAAGCCCCTCCGGGCAACTTCCACCGGAACCCCTTCTGGATCGATAGTTTTCGGGCATCTG  
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GCGCTGCCGTAAGAAGTTCTCCGGCGAGCTACATACCAGACATATGTGAAGATGCAGCCGTGGAAGGACTCCATCT  
GGCGGGTGACGTCTATGCTTTGAAGGGGATGACATTTATCGCTGTGTACGGGGGGTCAAGGTATGCTCTAAAT  
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TTGGGGAGAAGAAAGCTCTCCCGGATCAAGGTCCTGCTCCTCCCAAGCCCAACCCAGCAACGCACGTGCTGCA  
TCACCGGTGGTTGCACGGGCATTGGAGATCCTGGCTGCGGAGGTCGGTCTGTCCGAGGCTGAAATGACCGACAGTCT  
CAACTTCGCCGACTACGGGGTTCGACTCGCTGCTTTCTTTCAGCGGTGACCGGCAGGTATCGTGAAGAACTGAACCTTG  
ATCTGGAATCGTCCGTGTTTCATGGATTACCCGACCATCAAGGATTTCAAGGCCCTACCTGGCCGAGAAGGGCTTCTGC  
GACAGCAGCAGTCCCAGCCGTCAGCGAGCCCGAGTCCAAGTTCTCGTTCAACAGCGACGCATCATCCGAAGCTTC  
CAGCGGACTTACCCTCCTGGAATTACATCTCTGTGAAGCATGAGGCGCCCAAGGGCGGACAGAACAAGTCTGGA  
AAAGCATCTGCAGTATCATCGCCGAGGAAATCGGGGTGTCGGTTCGGAGACATTGACCCGAGCGACAACCTGCCAGAG  
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CGCCGGTCTCCGAACCCATCCGGCTCCTCGAGACAATCGACAACACGAAGCCCAAGACGTCTCGACATCCTCCGGCG  
ACCTCGATTCTTCTCCAGGGCAACCCCAACACCGCCACCAAGAAGCTCTTCATGTTCCCGGACGGCTCGGGCTCCGC  
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CTCAGAACCTCACGTGCAGTCTTGCAGAGCTGACCGAGCCCTATCTGGCGGAGATCCGCCGACGTGACCCCAAGGGA  
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AGTTCTCAACTCGATTGGGCTCTTTGGCGACGGAACTGGCCGCTCCCGACTGGCTCCTCCCACTTCTCTCGCC  
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GACCTACCTGATCTGGGCCAAGGACGGAGTCTGCGGCAAGCCGGGCGATCCCGCGCCGAGCCTGCAGAGGATGGAT  
CCGAGGACCCCGCGAAATGCAGTGGCTGCTCAACGACCGAACGGATCTGGGACCAAACAATGGGATACTTTGGTG  
GGCCCGCAAACATTGGCGGAATCCATGTGATGGAGGACGCGAATCATTTACCATGACGACGGGACAGAAGGCGAA  
GGAGTTGTGCAATTCATGGCCACGGCCATGAGTTCTAG

Description of construct designed to mutate *alb1* of *Aspergillus fumigatus*

The unshaded sequences are from *Aspergillus fumigatus alb1* to help direct the knockout construct to the *alb1* locus in the fungus. In this particular construct, the sequences with lighter gray shading are from the *alcA* gene of *Aspergillus nidulans* (GenBank: DQ076245.1), and the darker gray shaded sequences are from the *brlA* gene of *Aspergillus fumigatus* (GenBank: XM\_747933.1). The construct SEQ ID NO:7 was assembled from known sequences.

Nucleotide sequence of the *alb1* knock out construct

GATAGCGGCCGCTTGCAGGCGAAGAACCATACTATCGTTCGCTCGTTTCATCGAAAGATGCTTCCATGCACTGCGTC  
AGGAAATCACCAGGCTGCCGCTTCTCAGCGCACGCTCTTCCCGCGGTTTACCAGCATCGCCGACTTGTCTGCTCAG  
CATCGTGAGTCAGGGACAAACCCTGCGCTGGGGAGCGCGCTGACCTGTATCTATCAACTGGGGTGTTCATCGAGTA

AGTCGCCTTGCAAGGTATTCTGGACTGTGGCTGATCCTGGATAGTTACCACGGTGATCGTGACATCCATATCCGTC  
CTCGGATGACGGCCTTCTGGGTTTCATGTACGGGTATGTTGAGTTGCACCCGAGTCAGCTCGTGCAAGAATGTCCGAG  
AACTACTGCCGCTGGCAGTCGAGATTGTCAGATTGACTATCCACCTCGGGCTCTGTGTTCATGAGAGTCCGAGAGATG  
GTGGACTCGACGGAGTCATCCTCCGGCAGCTGGTCAATCCTCGTCTCGGAGATCAACGAGGCAGATGCCACCAGCCT  
GATTGGCAATTTTGTCAAGAAGCGAGTAAGTACAGTGTACGACCATTGGAAGAAGAATATTGACAATACCAGGGAAT  
TCCCCCTCGTCGCAACCGTACATCAGCGCGGTTGGATCGAAAGGCTCACCATCAGTGCACCACCCGAAATCTCG  
ACAACTTTATCGAAGAAGGTCTTCCGAAGGAGTACAAACACTTCAAGGCTCCTGGAGTCACTGGTCCGTACCACGCG  
CCCCATCTGTACAATGACCGAGAAATTCGCAATATCCTCAGCTTCTGTCTCCGAGGACGTGATTCTGCGCCACACACC  
ACGGGTTCCACTGGTCTCGAGCAACACAGGGAAGCTGGTCCAGGTAAGAGCATGCGTGATCTGTAAAGGTGGCTC  
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CACGGTCTAAGATCGCCATCATCGGAATGTCTGGGCGGTTCCCTGAGGCAGATGGTATCGAGGCTGGCGTTCCGTT  
CTGCTTAGGGTATTTGGGAACAATCAATGTTCAATGTACATTTAATCCACGATTTTATAAAAACGTCATCCTTTGCC  
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AATAACCCCCAGCTGAAAAGCTGATTGTGATAGTTCCCACTTGTCCGTCCGCATCGGCATCCGCAGCTCGGGATAGT  
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GTTCAAGAGGTACGCGTATAGAGCCGTATAGAGCAGAGACGGAGCACTTTCTGGTACTGTCCGCACGGGATGTCCGC  
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AACTCTTCCAATCCTATCACCTCGCCTCAAAATGAGATCCCAGGGTAATATGTCTGATCGCCTGGGCGTGAAGTGG  
ACTGCCACTCACTCGGCTCCAACGAATGTCCGCTTATGGGCTCCAGCTTCTCGCCTTTTGGAAATCGCCACACCTACC  
CCTACGAGCATCTACAGTCAAGGTTCACTTGCCTTCCCAAGCTGGCCAGAAAACGGGTCAATACCCCGGACACCGTTA  
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CGTGCCTGTGCGGCCCTATCTCCCATCATCAACCCGAGCGGCTGCCACCATCGTTATCCATGAGCCATATGRTGCC  
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GCAGTGTCTTGGAGCGACACACCTTTGAGCCGTTCTCTCTGGCGGGCGCTGGTGAGTACATGGATGAATGCCACCAG  
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CAAGCAGAGCTTGTCACTAGAGAACCTGCCATCCATCATCAAGCAGGTTGAGTTCAAGTGCAAAAGAACCTGGCTGCA  
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ATAGTCTGGGAGACTACGCAGCGTTGAACAGTGCGGGCGTCTTGTCCACCAGCGATACGATTTACCTCTGTGGCCGT  
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TCAACATCTGCTCGATCCAGACGTCCACGCCGTCGCTGCATCAATGGACCAACCGAAACGGTCAATCAGCGGGCTCA  
GCGGTGCAATCGATGAATTGGCACAGCAGTGTCCAGCCAAAATCTCAAGTCCACCAAGCTCAAAGTGCCGTTCCGCG  
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CGTCCCGTTCGTCTCTGCTCTGAACGGAGAGGTAATCACGGAGTGAACACAGCGTGTGGGCCCCACGTATATGG  
TGAAGCATTGTCCGGAAGCCGTCATTTCTTGGCGCTCTTGGAGCGACCCGGCACGCCAAGTTGATGGATGACGCC  
ACACTCTGGGTGCAAGTGGGATCCCATCCATTTGCTCGGGTATGATCAAGTCCACCTTTGGCGGCCGACAG

Whereas particular embodiments of this invention have been described for purposes of illustration, it will be understood by those persons skilled in the art that numerous variations of the details of the present invention may be made without departing from the invention as defined in the appended claims.

What is claimed is:

1. A strain of fungus comprising *Aspergillus fumigatus* (*A. fumigatus*) and expressing one or more genes of the ergot alkaloid biosynthesis pathways from one or more fungus selected from the group consisting of:
  - a. *Epichloë festucae* var. *lolii* x *Epichloë typhina* isolate Lp1 (*E. sp.* Lp1);
  - b. *Claviceps* species;
  - c. *Claviceps africana* (*C. africana*);
  - d. *Claviceps gigantea* (*C. gigantea*);
  - e. *Periglandula* species; and
  - f. *Epichloë coenophiala*wherein gene *easA* or gene *easM* is inactivated in said *A. fumigatus*.
2. The strain of Claim 1, wherein said one or more genes of the ergot alkaloid biosynthesis are selected from the group consisting of:
  - a. *easA*; and
  - b. *cloA*.
3. The strain of Claim 2, wherein said gene *easA* is inactivated in said *A. fumigatus*, and said one or more fungus is *E. sp.* Lp1.
4. The strain of Claim 2, wherein said gene *easA* is inactivated in said *A. fumigatus*, and said one or more fungus is a *Periglandula* species or *Epichloë coenophiala* that produces lysergol.
5. The strain of Claim 2, wherein said gene *easA* is inactivated in said *A. fumigatus*, and said one or more fungi are a *Periglandula* species or *Epichloë coenophiala* and *E. sp.* Lp1, wherein said expressing gene *easA* is from a *Periglandula* species or *Epichloë coenophiala* and said expressing gene *cloA* is from *E. sp.* Lp1.

6. The strain of Claim 2, wherein said gene *easA* is inactivated in said *A. fumigatus*, and said one or more fungi are a *Periglandula* species or *Epichloë coenophiala* and *E. sp. Lp1*, wherein said expressing gene *cloA* is from a *Periglandula* species or *Epichloë coenophiala* and said expressing gene *easA* is from *E. sp. Lp1*.
7. The strain of Claim 2, wherein said gene *easM* is inactivated in *A. fumigatus*, said one or more fungus is *E. sp. Lp1*, and said expressing one or more genes of the ergot alkaloid biosynthesis is *cloA*.
8. The strain of Claim 2, wherein said gene *easM* is inactivated in *A. fumigatus*, said one or more fungus is *C. africana*, and said expressing one or more genes of the ergot alkaloid biosynthesis is *cloA*.
9. The strain of Claim 2, wherein said gene *easM* is inactivated in said *A. fumigatus*, said one or more fungus is *C. gigantea*, and said expressing one or more genes of the ergot alkaloid biosynthesis is *cloA*.
10. A method for producing lysergic acid comprising inactivating an ergot alkaloid biosynthesis pathway gene from the fungus *A. fumigatus* and expressing genes *easA* and *cloA* from the fungus *E. sp. Lp1*, wherein said inactivated ergot alkaloid biosynthesis pathway gene is *easA* of *A. fumigatus*.
11. A method for producing novel ergot alkaloids comprising inactivating an ergot alkaloid biosynthesis pathway gene from the fungus *A. fumigatus* and expressing genes *easA* and *cloA* from the fungus *E. sp. Lp1*, wherein said inactivated ergot alkaloid biosynthesis pathway gene is *easA* of *A. fumigatus*.
12. A method for producing dihydrolysergic acid (DHLA) comprising inactivating gene *easM* in *A. fumigatus* and expressing gene *cloA* from *E. sp. Lp1* or gene *cloA* from *C. africana* in said *A. fumigatus* strain.

13. A method for producing dihydrolysergol (DHlysergol) comprising inactivating gene *easM* in *A. fumigatus* and expressing one or more genes of the ergot alkaloid biosynthesis from *C. gigantea* selected from the group consisting of:

a. *cloA*; and

b. *cloA* and *easA*,

wherein said gene(s) from *C. gigantea* are expressed in said *A. fumigatus* strain.

14. A strain of fungus comprising a species of a fungus and expressing one or more genes of the ergot alkaloid biosynthesis pathways from one or more of said fungus, wherein said fungus has a pathway similar to *A. fumigatus*.

15. The strain of Claim 14, wherein said one or more genes of the ergot alkaloid biosynthesis are selected from the group consisting of:

a. *easA*; and

b. *cloA*.

16. The strain of Claim 15 wherein said *easA* or *cloA* genes from said ergot alkaloid producing fungi are functionally similar to the genes from *Claviceps purpurea* or any of *Epichloe* species.

17. A method of producing ergot alkaloids in *A. fumigatus* comprising expressing ergot alkaloid synthesis genes from other fungi in *A. fumigatus* *easA* knockout or *easM* knockout, allowing native prenyl transferase EasL act on any ergot alkaloids so produced for producing prenylated alkaloids.

18. A method of producing ergot alkaloids in a strain of *A. fumigatus* comprising expressing a bidirectional *easA/easG* promoter of *A. fumigatus* to drive expression of oxidase genes in the *A. fumigatus* *EasA* knock-out background.

19. The method of 18, wherein a EasA gene from *E. sp. Lp1* is expressed in said *A. fumigatus* EasA knock-out background.
20. The method of claim 19, wherein said EasA gene from *E. sp. Lp1* includes expression of cloA.
21. A method for the production of lysergic acid comprising providing for the expression of EasA/CloA in *A. fumigatus* easA knockout.
22. A method of producing a festuclavine-accumulating strain of *A. fumigatus* comprising a knock-out of the easM allele.
23. A method for producing lysergic acid in *A. fumigatus* easA knock-out providing amplifying *E. sp. Lp1* easA and *E. sp. Lp1* cloA for producing lysergic acid.
24. A method for accumulating lysergol comprising amplifying easA and cloA from *Periglandula* in plant material selected from the group consisting of *Stictocardia tiliifolia*, *S. beraviensis*, *Argyreia*, and *Ipomoea* species or by amplifying easA and cloA from *Epichloë coenophiala* for accumulating lysergol.
25. A method for producing lysergol comprising providing expressing *Periglandula sp.* easA and *P. sp.* cloA or *Epichloë coenophiala* easA and *Epichloë coenophiala* cloA in a *A. fumigatus* easA knock-out strain for producing lysergol.
26. A method for producing lysergol comprising expressing *P. sp.* easA or *Epichloë coenophiala* easA and *Epichloë sp. Lp1* cloA in a *A. fumigatus* easA knock-out strain for producing lysergol.
27. A method for producing lysergol comprising *A. fumigatus* easA knock-out strain through expression of *E. sp. Lp1* easA and *P. sp.* cloA or *Epichloë coenophiala* cloA for producing lysergol.

28. The method according to claims 26, 27, and 28, including amplifying said easA and cloA based on degenerate primers designed to anneal to versions of each gene.
29. A method for producing dihydrolysergic acid comprising expressing *C. africana* cloA under the control of a *A. fumigatus* easA promoter in *A. fumigatus* easM knock-out strain for producing dihydrolysergic acid.
30. A method for producing dihydrolysergic acid comprising expressing *C. africana* easA, *C. africana* cloA, and *E. sp.* Lp1 cloA using a *A. fumigatus* easA/easG promoter for producing dihydrolysergic acid.
31. A method for producing dihydrolysergol comprising expressing *C. gigantea* cloA in *A. fumigatus* easM knock-out for producing dihydrolysergol.
32. The method of claim 31, including joining said cloA to a easA promoter of *A. fumigatus* to form a cloA construct and introducing said cloA construct into *A. fumigatus* easM knock-out utilizing cotransformation with pBCphleo.
33. The method of embodiment 32 set forth above, including adding a *C. gigantea* easA expressed from a *A. fumigatus* easA promoter to said cotransformation of the *A. fumigatus* easM knockout.
34. A strain of fungus comprising SEQ ID NO:4.
35. A strain of fungus comprising SEQ ID NO:7.

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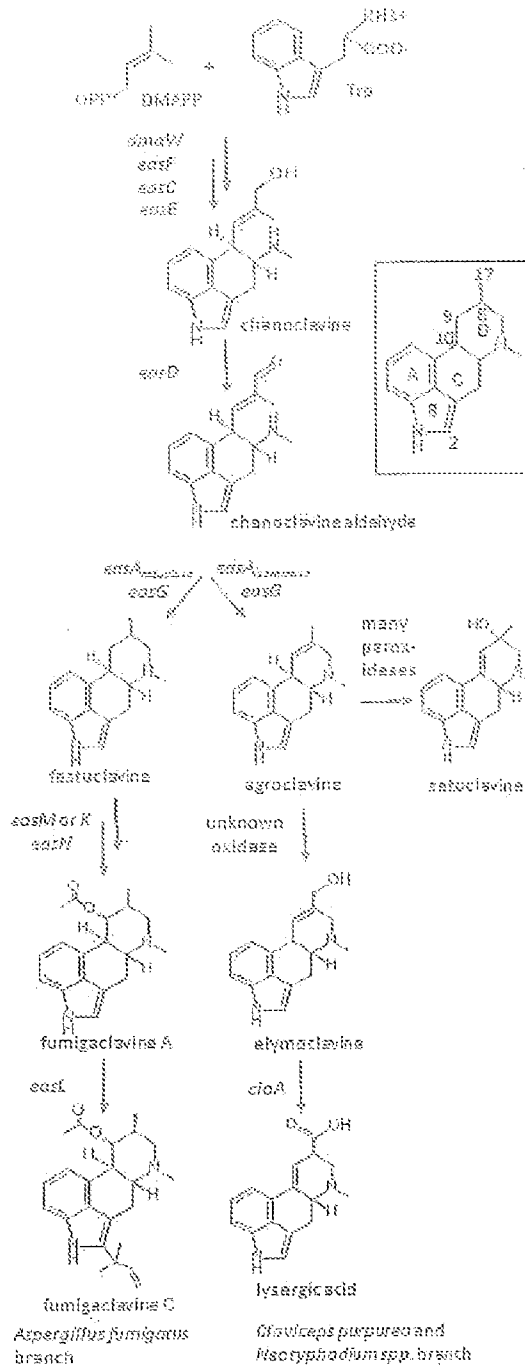


FIGURE 1



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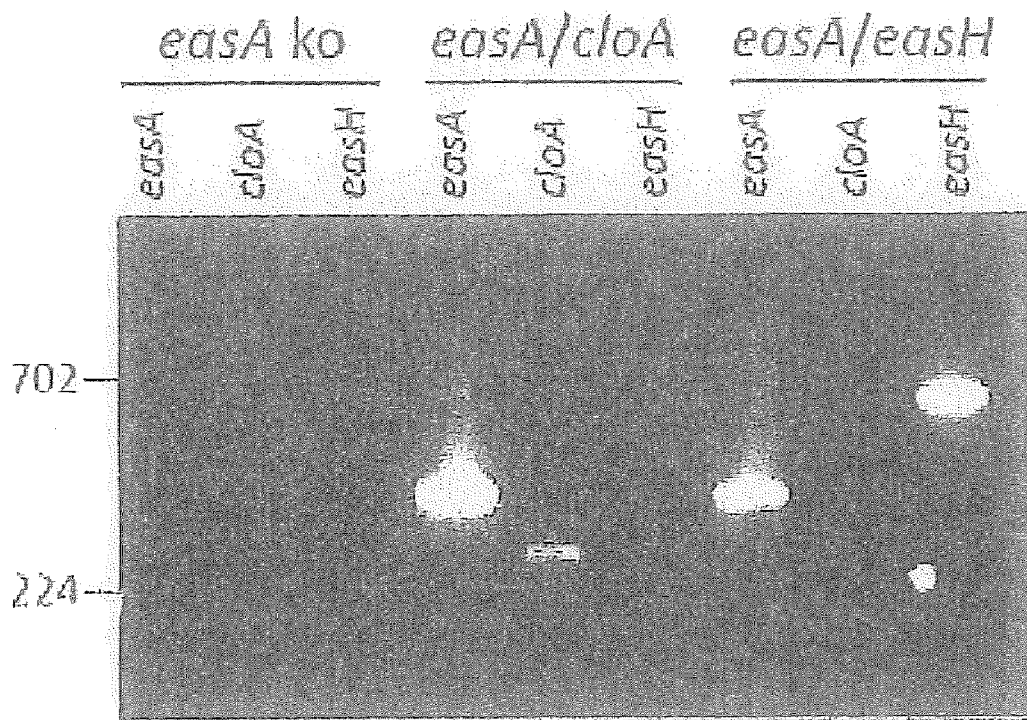


FIGURE 3

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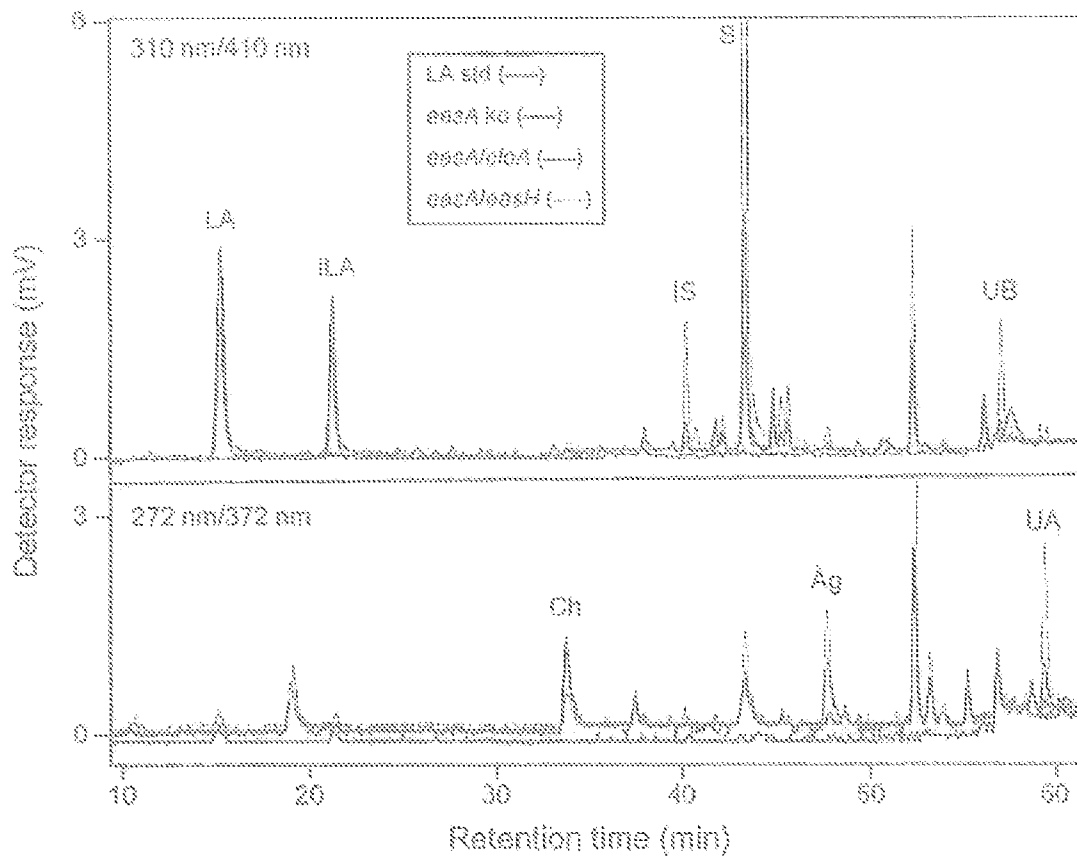


FIGURE 4

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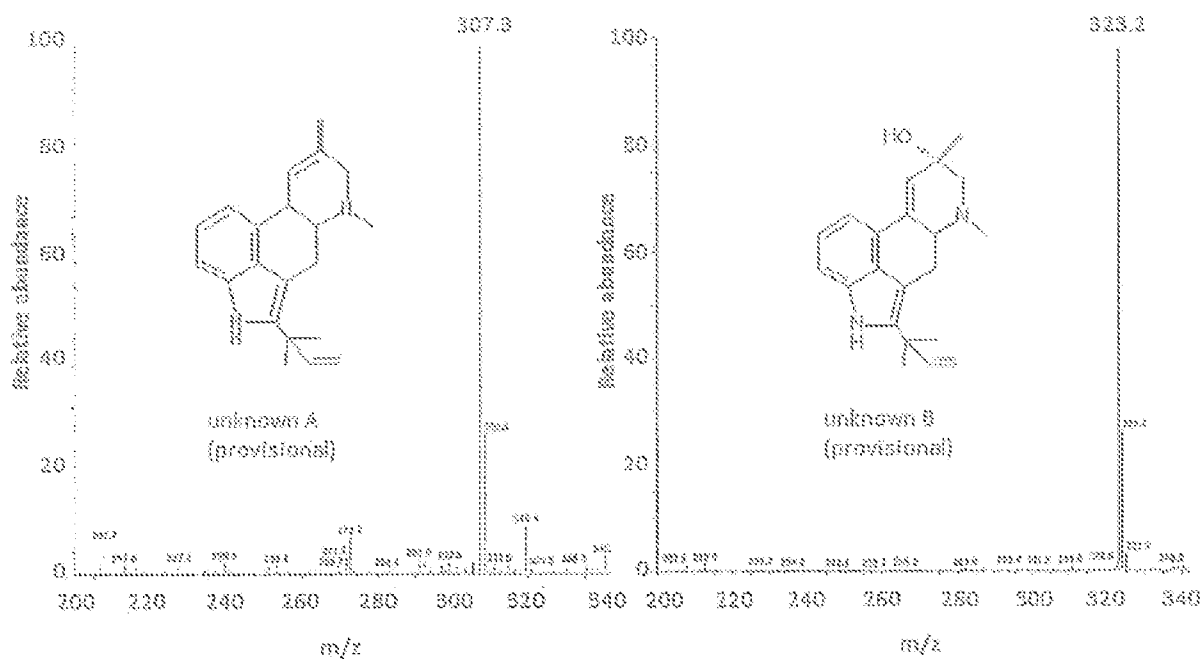


FIGURE 5

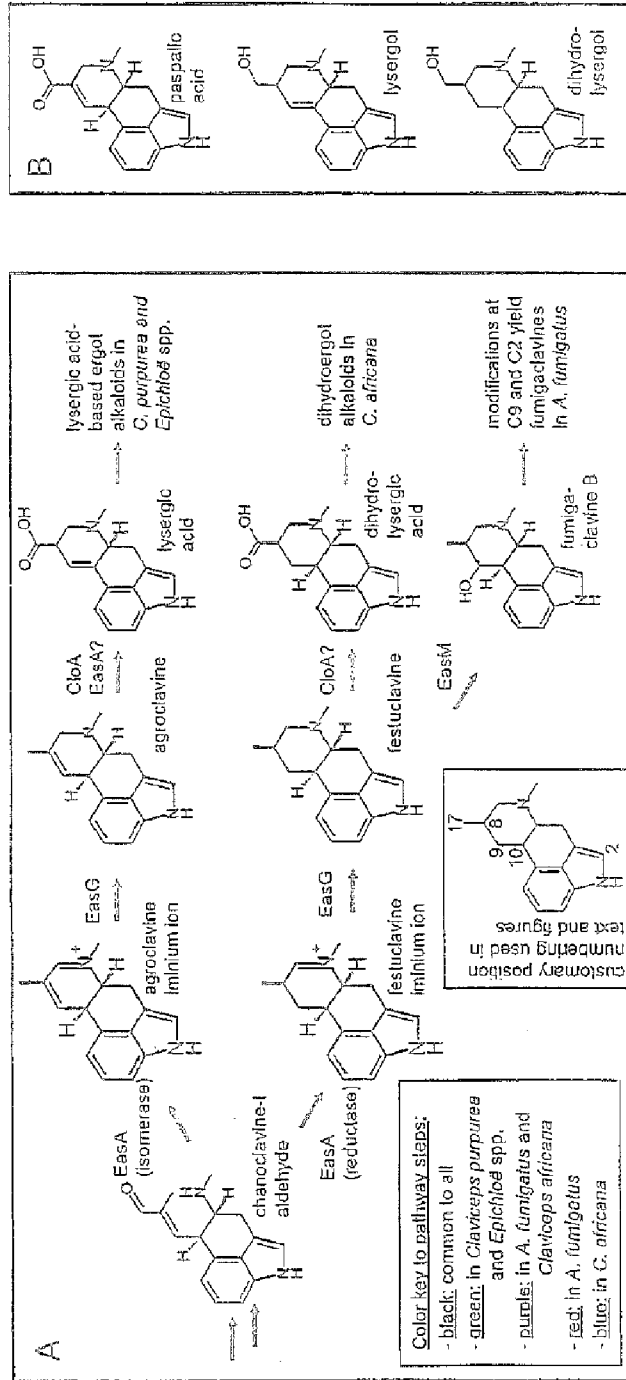


FIGURE 6

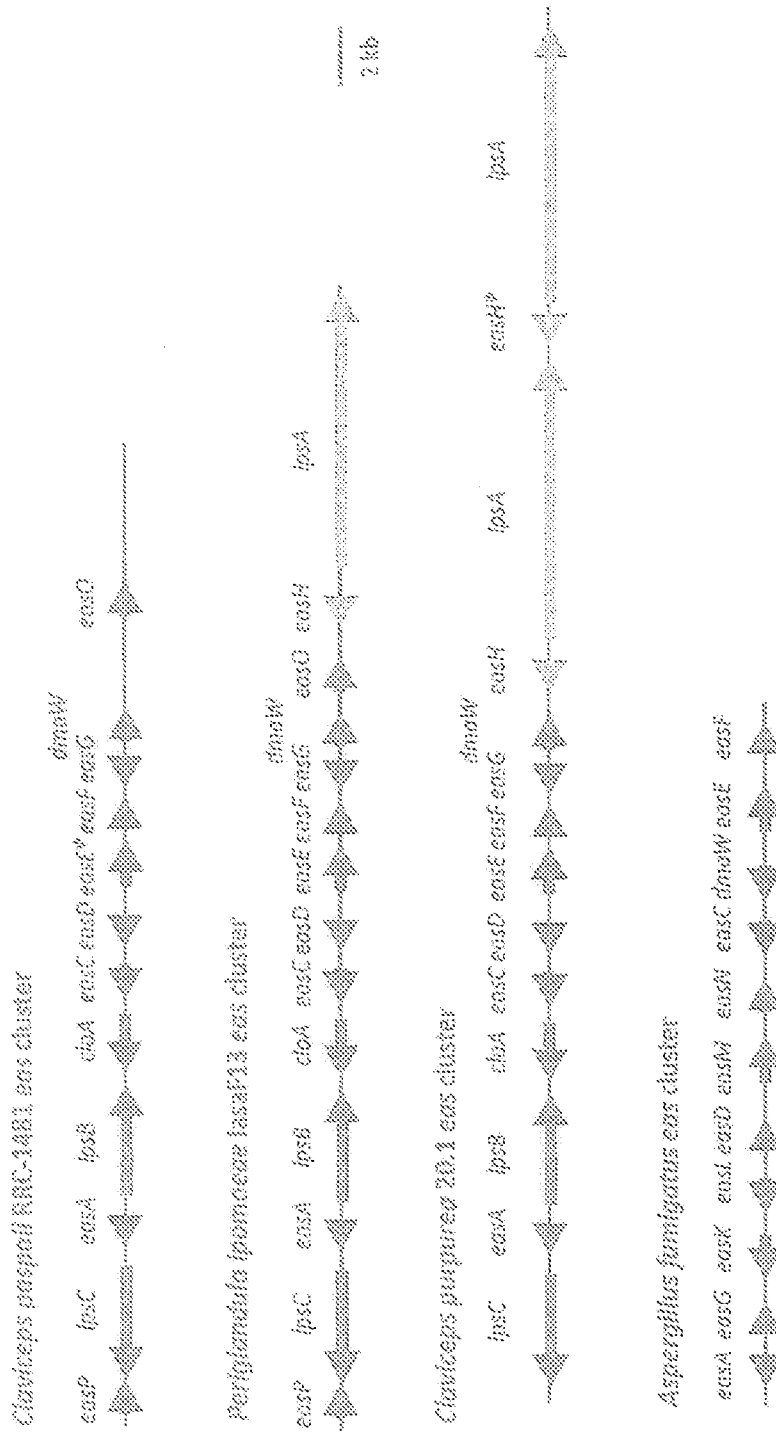


FIGURE 7

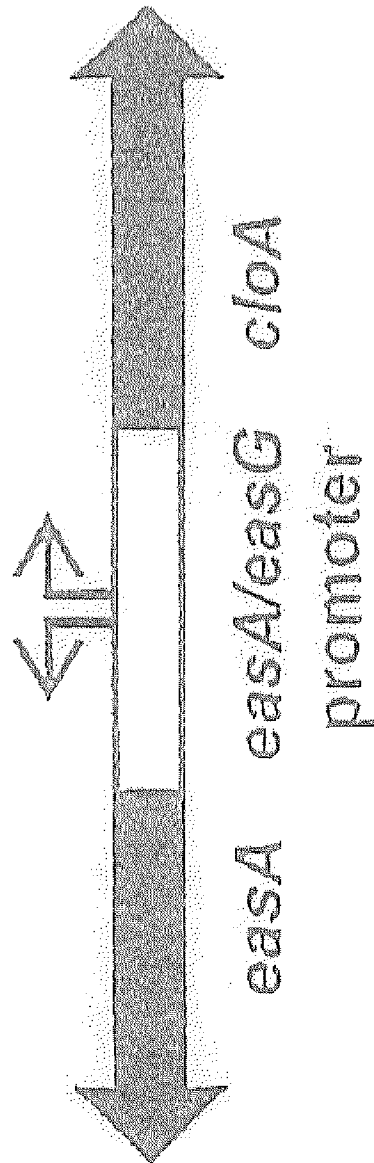


FIGURE 8

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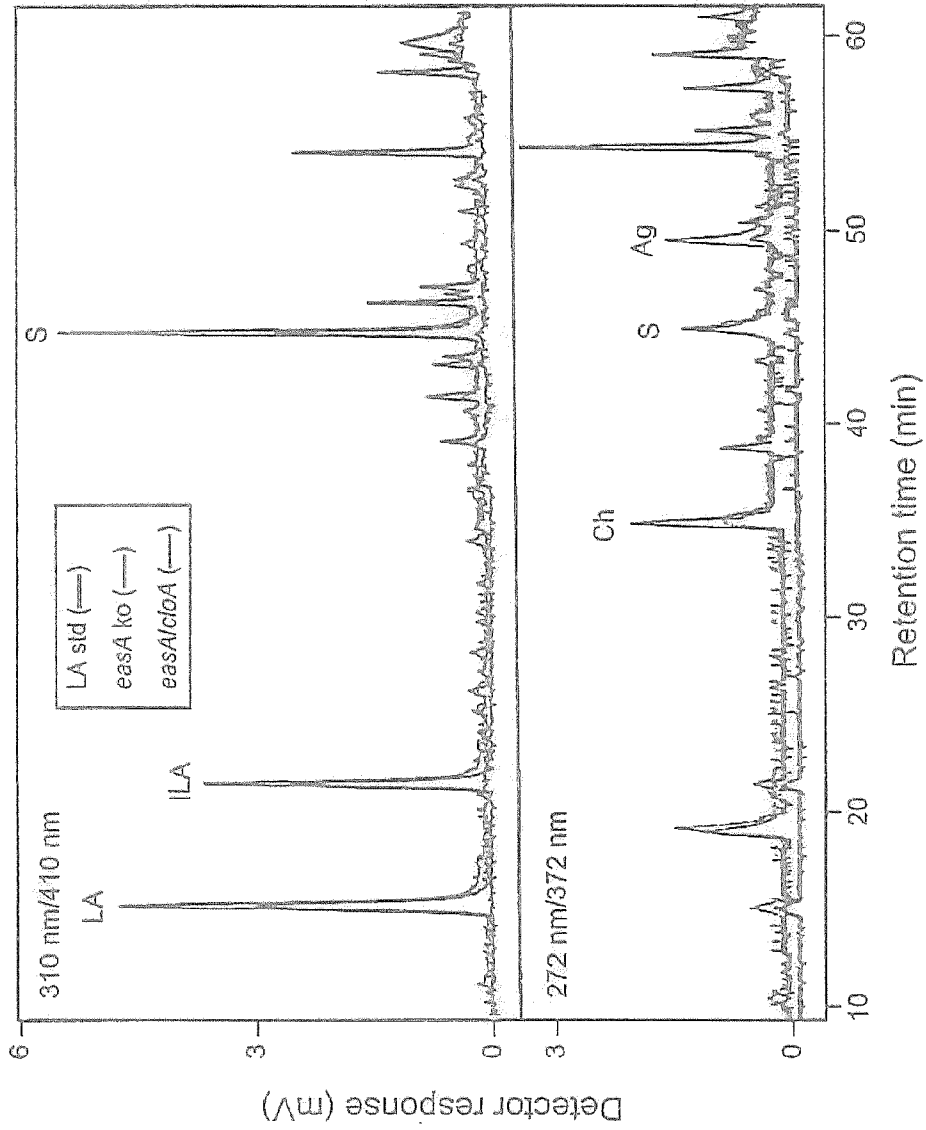


FIGURE 9



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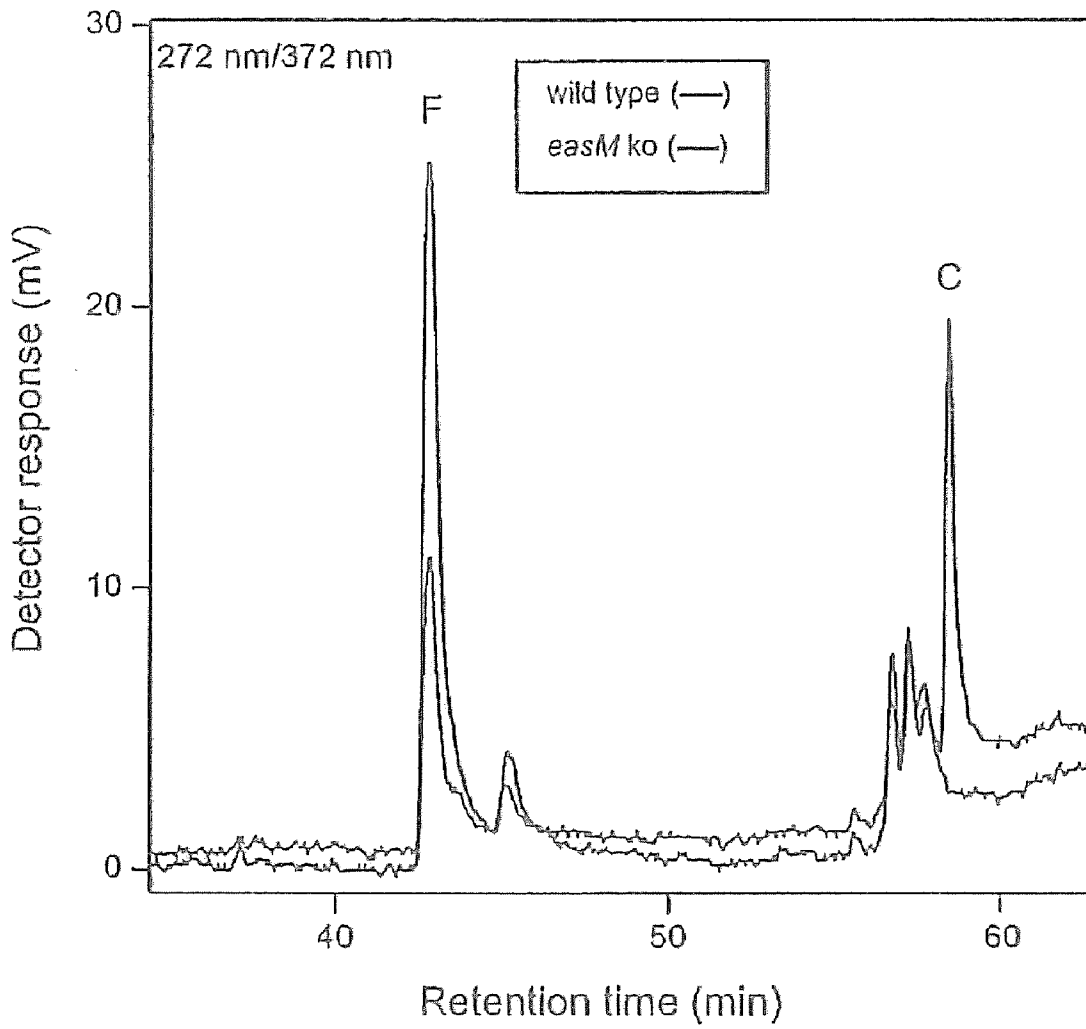


FIGURE 11

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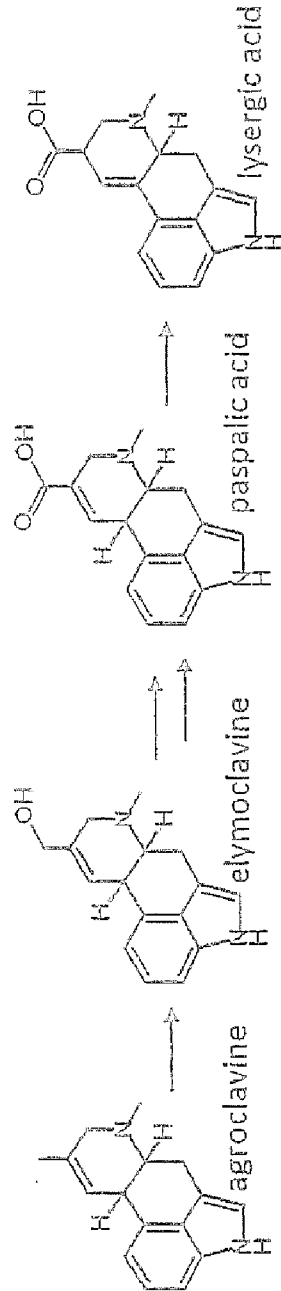


FIGURE 12

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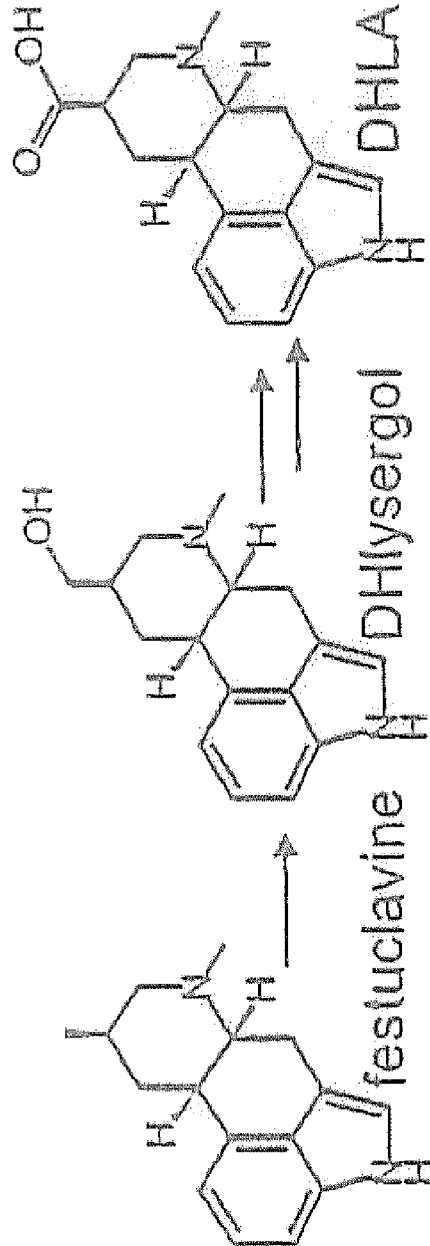


FIGURE 13

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*Aspergillus fumigatus* ergot alkaloid pathway

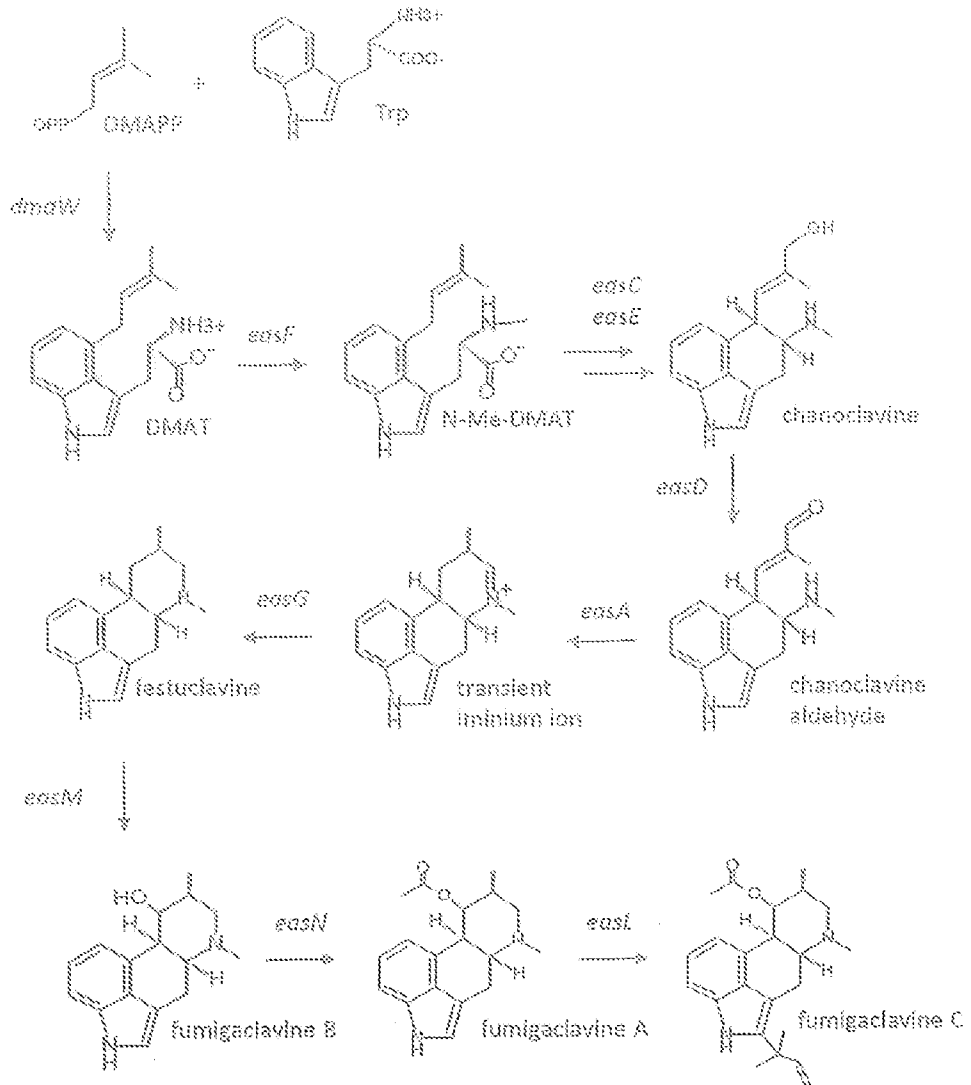


FIGURE 14