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(54) Titre : INHIBITEURS DU METABOLISME DES STEROLS DESTINES A ETRE UTILISES POUR L'ACCUMULATION DE TRIGLYCERIDES DANS LES MICROALGUES, ET PROCEDES ASSOCIEES
(54) Title: INHIBITORS OF STEROL METABOLISM FOR THEIR USE TO ACCUMULATE TRIGLYCERIDES IN MICROALGAE, AND METHODS THEREOF

(57) Abrégé/Abstract:

The invention relates to a method for accumulating triacylglycerols in microalgae by inhibiting the sterol metabolism, by incubating the microalgae with an inhibitor of sterol metabolism. The invention also relates to a method for producing fatty acids, biofuels, pharmaceutical or cosmetic compositions, and also food supplements, comprising a triacylglycerols accumulation step in microalgae according to the invention. Finally, the invention concerns the use of an inhibitor of sterol metabolism to accumulate triglycerides in microorganisms, and preferably microalgae.

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(57) Abstract: The invention relates to a method for accumulating triacylglycerols in microalgae by inhibiting the sterol metabolism, by incubating the microalgae with an inhibitor of sterol metabolism. The invention also relates to a method for producing fatty acids, biofuels, pharmaceutical or cosmetic compositions, and also food supplements, comprising a triacylglycerols accumulation step in microalgae according to the invention. Finally, the invention concerns the use of an inhibitor of sterol metabolism to accumulate triglycerides in microorganisms, and preferably microalgae.



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INHIBITORS OF STEROL METABOLISM FOR THEIR USE TO ACCUMULATE TRIGLYCERIDES IN MICROALGAE, AND METHODS THEREOF

The invention relates to a method for accumulating triacylglycerols in microalgae by inhibiting the sterol metabolism. The invention also relates to a method for producing fatty acids, biofuels, pharmaceutical or cosmetic compositions, and also food supplements, comprising a triacylglycerols accumulation step in microalgae according to the invention. Finally, the invention concerns the use of an inhibitor of sterol metabolism to accumulate triglycerides in microorganisms, and preferably microalgae.

It is acknowledged that oilseed production from crops cannot be diverted from nutritional purpose (Durrett *et al.*, The Plant Journal (2008) 54, 593-607). Therefore, efforts are directed towards the oil production in other organisms like algae (Chisti, Biotechnology Advances 25 (2007) 294-306; Chisti, Trends in Biotechnology, 2008, Vol 26, No. 3; Dismukes *et al.*, Current Opinion in Biotechnology 2008, 19:235-240; Scott *et al.*, Current Opinion in Biotechnology 2010, 21:277-286; Singh *et al.*, Bioresource Technology 102 (2011) 26-34). Studies undergone on triacylglycerol (TAG, also called oil) production in algae (Table 1 below) have focused on the increase of TAG in cytosolic droplets.

Table 1: Oil content of some algae (from Chisti, Biotechnology Advances 25 (2007) 294-306)

Microalga	Oil content (% dry wt)
<i>Botryococcus braunii</i>	25–75
<i>Chlorella</i> sp.	28–32
<i>Cryptocodinium cohnii</i>	20
<i>Cylindrotheca</i> sp.	16–37
<i>Dunaliella primolecta</i>	23
<i>Isochrysis</i> sp.	25–33
<i>Monallanthus salina</i>	>20
<i>Nannochloris</i> sp.	20–35
<i>Nannochloropsis</i> sp.	31–68
<i>Neochloris oleoabundans</i>	35–54
<i>Nitzschia</i> sp.	45–47
<i>Phaeodactylum tricornutum</i>	20–30
<i>Schizochytrium</i> sp.	50–77
<i>Tetraselmis sueica</i>	15–23

The advantages of microalgae over land plants have been summarized in the EPOBIO report (Micro- and macro-algae: utility for industrial application, September 2007, Editor: Dianna Bowles). Both plants (crops) cultivable on arable lands and microalgae grown in open ponds or in confined reactors are potential sources of TAG and fatty acids for industrial purposes and biofuels (Dismukes *et al.*, Current Opinion in Biotechnology 2008, 19:235-240).

However, serious concerns have been raised by the intensive agricultural practices the use of crops implies and the diversion of crops from food to non-food chains. Efforts are thus needed to develop novel generation biofuels based on photosynthetic microorganisms.

The main advantages of microalgae in relation to plants for the production of TAG are the following:

- This bioresource does not compete with the agro-resources used for animal or human nutrition.
- Algal growth can be monitored in controlled and confined conditions in an environmental friendly process using recycled inorganic and organic wastes generated by other human activities and the use of microalgae allows trapping and converting industrial byproduct gases (*e.g.* CO₂) into valuable organic molecules (Chisti, *Biotechnology Advances* 25 (2007) 294-306; Chisti, *Trends in Biotechnology*, 2008, Vol 26, No. 3; Chisti, *Journal of Biotechnology* 167 (2013) 201-214).
- The algal biomass productivity is high, microalgae showing a very high potential of productivity with cost savings when compared to land plants (see Table 2). Their yield is variable and determined by the culturing approach employed: it is relatively low in open pond systems while it can be significantly increased in closed photobioreactors where culture parameters can be controlled.
- This bioresource does not depend on a geographical location, or on a season.

Table 2: Comparison of biomass productivity of major crops ("C₃" or "C₄" type photosynthesis) and microalgae (extract from the « EPOBIO project » report, University of York (09/2007), Table 4).

	Microalgae	"C ₄ " crops (sorghum, maize, sugarcane...)	"C ₃ " crops (wheat, sunflower...)
Maximal productivity (T.ha ⁻¹ .y ⁻¹)			
Microalgae (photobioreactors)	130 to 150	-	-
Higher plants (maximum productivity)	-	72	30
Average productivity in production systems (T.ha ⁻¹ .y ⁻¹)			
Microalgae (large scale)	10 to 50	-	-
Higher plants (field)	-	10 to 30	8 to 18
Biomass production costs (USD.kg ⁻¹)	0.4 - 40	0.04	0.04

The economic viability of this sector of bioindustry is challenged by the current limitation to combine the overall biomass yield, *i.e.* dry weight of algal organic matter produced per liter and the proportion of valuable molecules, *i.e.* sufficiently high proportion of TAG per dry weight for industrial extraction and processing (Chisti, Biotechnology Advances 25 (2007) 294-306; Chisti, Trends in Biotechnology, 2008, Vol 26, No. 3; Chisti, Journal of Biotechnology 167 (2013) 201-214).

In particular, the lipid composition of microalgae is compatible with biodiesel production (Dismukes *et al.*, Current Opinion in Biotechnology 2008, 19:235-240; Scott *et al.*, Current Opinion in Biotechnology 2010, 21:277-286). The rationale for producing biodiesel from microalgae is to use sunlight to convert water and carbon dioxide into biomass. This biomass is then specifically redirected towards the synthesis of oil for the generation of biofuels, by applying external stimuli like nutrient stresses, and/or by genetic engineering of metabolism (Dorval Courchesne *et al.*, Journal of Biotechnology 141 (2009) 31-41).

The three most important classes of micro-algae in terms of abundance are the diatoms (Bacillariophyceae), the green algae (Chlorophyceae), and the golden algae (Chrysophyceae) (EPOBIO definition). Diatoms are a major phylum of the phytoplankton biodiversity in oceans, fresh water and various soil habitats. They are responsible for up to 25% of the global primary productivity. Study of this group of eukaryotes has benefited from recent developments on *Phaeodactylum tricornutum*, a model of pennate diatoms. Diatoms, like other microalgae, are considered a plausible alternative source of hydrocarbons to replace fossil fuels or chemicals from petrochemistry, with the advantage of having a neutral CO₂ balance, based on the hypotheses that CO₂ and water can be efficiently converted into biomass by photosynthesis and that the carbon metabolism could be controlled so that they accumulate energetically-rich TAG. Different phytoplanktonic organisms of the Chromalevolata superphylum have focused the attention for their ability to accumulate TAG, with promising initial yields and appropriate robustness and physical properties to be implemented in an industrial process, including *Phaeodactylum tricornutum*. *Phaeodactylum tricornutum* is currently used for the industrial production of omega-3 polyunsaturated fatty acids but industrial implementation for this application and for other applications such as biofuels is still limited by the growth retardation and low yield in biomass when TAG accumulation is triggered using conventional nutrient starvation approaches, such as nitrogen starvation (Chisti, Journal of Biotechnology 167 (2013) 201-214). These approaches have an important drawback which is the limitation of growth that the nitrogen starvation induces. *Phaeodactylum tricornutum* exhibits interesting properties for an industrial implementation,

like the ability to grow in the absence of silicon or the sedimentation of cells that could be useful for harvesting techniques. Attempts to promote TAG accumulation can rely on various strategies that can be combined, including the stimulation of fatty acid and TAG biosynthesis, the blocking of pathways that diverts carbon to alternative metabolic routes and eventually the arrest of TAG catabolism. Small molecules could act on each of these three aspects of TAG metabolism.

It is possible to promote the accumulation of oil in microorganisms by inhibiting or blocking metabolic pathways that direct the carbon fluxes to alternative metabolites. For instance, it is well known that blocking the accumulation of carbohydrate in storage sugars such as starch, promotes the accumulation of oils (Siaut *et al.*, BMC Biotechnology 2011, 11:7).

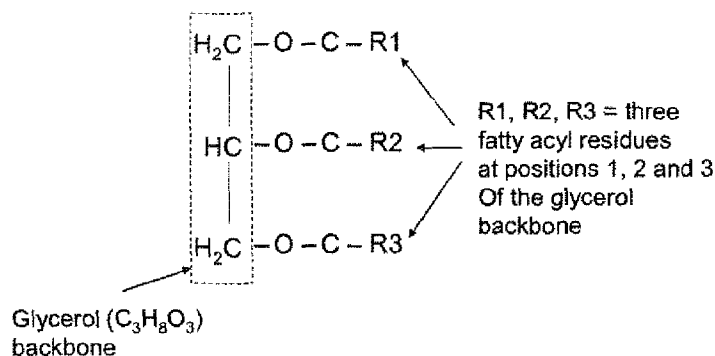
However, there remains a need for alternative methods to trigger the accumulation of oil when algae are grown in a nitrogen-rich medium, and by trying to avoid blocking carbohydrate storage metabolism. Indeed, the carbohydrates produced after CO₂ photosynthetic conversion serve as a source of carbon for all other organic molecules within the cell, so blocking their storage has a very strong negative impact on cell growth. Other metabolic pathways using carbon might be blocked and allow a redirection of carbon metabolism towards TAG metabolism.

In this aim, the Inventors have now identified that the metabolism of sterols is an alternative sink of carbon, its inhibition in microalgae triggering the accumulation of oils.

Therefore, a first subject of the invention is a method for triggering TAG accumulation in microalgae by inhibiting the sterol metabolism, preferably by inhibiting the synthesis of the sterols, said method overcoming the disadvantages listed above by incubating the microalgae with an inhibitor of sterol metabolism.

Within the framework of the invention, the term microalgae refers to microalgae for eukaryotes.

Also in the sense of the present invention, the TAG is built by esterification of a 3-carbon glycerol backbone at positions 1, 2 and 3 by fatty acids. Below, TAG is synthesized by esterification of a glycerol backbone by three fatty acids (R₁, R₂, R₃).



In the sense of the present invention:

- Alkyl groups are chosen among ($\text{C}_1\text{-C}_{26}$)alkyl groups, preferably ($\text{C}_1\text{-C}_{18}$)alkyl groups, and more preferably ($\text{C}_1\text{-C}_6$)alkyl groups such as methyl, ethyl, n-propyl, isopropyl, n-butyl, *sec*-butyl, *tert*-butyl and isobutyl radicals;
- Alkenyl groups are chosen among hydrocarbon chains of 2 to 26 carbon atoms, preferably 2 to 18, and more preferably 1 to 6, having at least one carbon-carbon double bond. Examples of alkenyl groups include ethenyl, propenyl, isopropenyl, 2,4-pentadienyl;
- Alkynyl groups are chosen among hydrocarbon chains of 2 to 26 carbon atoms, preferably 2 to 18, and more preferably 1 to 6, having at least one carbon-carbon triple bond;
- Alkylalkenyl means any group derived from an alkenyl group as defined above wherein a hydrogen atom is replaced by an alkyl group;
- Alkynylalkenyl means any group derived from an alkenyl group as defined above wherein a hydrogen atom is replaced by an alkynyl group;
- Cycloalkyl groups refer to a monovalent cyclic hydrocarbon radical preferably of 3 to 7 ring carbons. The cycloalkyl group can have one or more double bonds and can optionally be substituted. The term "cycloalkyl" includes, for examples, cyclopropyl, cyclohexyl, cyclohexenyl and the like;
- Heteroalkyl groups mean alkyl groups as defined above in which one or more hydrogen atoms to any carbon of the alkyl is replaced by a heteroatom selected from the group consisting of N, O, P, B, S, Si, Sb, Al, Sn, As, Se and Ge. The bond between the carbon atom and the heteroatom may be a single or a double bond. Suitable heteroalkyl groups include cyano, benzoyl, methoxy, acetamide, borates, sulfones, sulfates, thianes, phosphates, phosphonates, and the like;
- Alkoxy groups are chosen among ($\text{C}_1\text{-C}_{20}$)alkoxy groups, and preferably ($\text{C}_1\text{-C}_4$)alkoxy groups such as methyloxy, ethyloxy, n-propyloxy, iso-propyloxy, n-butyloxy, *sec*-butyloxy, *tert*-butyloxy and isobutyloxy radicals;
- Aryl groups means any functional group or substituent derived from at least

one simple aromatic ring; an aromatic ring corresponding to any planar cyclic compound having a delocalized π system in which each atom of the ring comprises a p-orbital, said p-orbitals overlapping themselves. More specifically, the term aryl includes, but is not limited to, phenyl, biphenyl, 1-naphthyl, 2-naphthyl, anthracyl, pyrenyl, and the substituted forms thereof;

- Heteroaryl groups means any functional group or substituent derived from at least one aromatic ring as defined above and containing at least one heteroatom selected from P, S, O and N. The term heteroaryl includes, but is not limited to, furan, pyridine, pyrrole, thiophene, imidazole, pyrazole, oxazole, isoxazole, thiazole, isothiazole, tetrazole, pyridazole, pyridine, pyrazine, pyrimidine, pyridazine, benzofurane, isobenzofurane, indole, isoindole, benzothiophene, benzo[c]thiophene, benzimidazole, indazole, benzoxazole, benzisoxazole, benzothiazole, quinoline, isoquinoline, quinoxaline, quinazoline, cinnoline, purine and acridine. The aryl and heteroaryl groups of the invention comprise preferably 1 to 12 carbon atoms, and more preferably 5 or 6 carbon atoms;

- Arylalkyl means any group derived from an alkyl group as defined above wherein a hydrogen atom is replaced by an aryl or a heteroaryl group;

- Arylalkenyl means any group derived from an alkenyl group as defined above wherein a hydrogen atom is replaced by an aryl or a heteroaryl group;

- Arylalkynyl means any group derived from an alkynyl group as defined above wherein a hydrogen atom is replaced by an aryl or a heteroaryl group;

- Alkylaryl means any group derived from an aryl group as defined above wherein a hydrogen atom is replaced by an alkyl group.

According to the invention, halogen atoms are chosen among bromine, chlorine, fluorine and iodine, and preferably bromine, chlorine and fluorine.

The acid addition salts of the inhibitor of sterol metabolism according to the invention may be for example chosen among hydrochloride, hydrobromide, sulphate or bisulphate, phosphate or hydrogenophosphate, acetate, benzoate, succinate, fumarate, maleate, lactate, citrate, tartrate, gluconate, methanesulphonate, benzene-sulphonate and paratoluene-sulphonate.

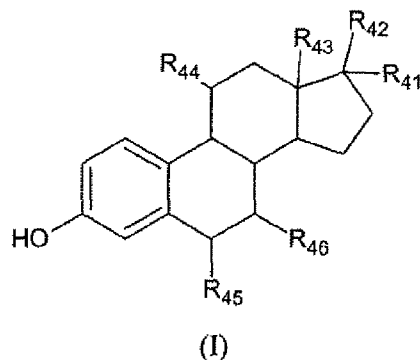
According to a preferred embodiment, in the method of the invention the inhibition of the sterol metabolism is realized by incubating the microalgae with an inhibitor of sterol metabolism in a nitrogen medium.

The concentration of the inhibitor of sterol metabolism may range from 1 μ M to 1M, and preferably from 5 to 20 μ M. The incubation step lasts preferably from 24 to 72 hours.

The microalgae of the invention is advantageously selected from microalgae of the diatom phylum, the Chromalveolata phylum, and the Archaeplastidae phylum, and more advantageously from microalgae of the diatom phylum and the Chromalveolata phylum. Preferably, the microalgae is selected from the diatom micro-algae species *Phaeodactylum* 5 *tricornutum* and *Thalassiosira pseudonana*, the Chromalveolata micro-algae species *Nannochloropsis*, and more preferably *Nannochloropsis gaditana*, *Nannochloropsis oceanica*, *Nannochloropsis salina*, and the Archaeplastidae micro-algae species *Chlamydomonas*, *Ostreococcus*, *Chlorella*. More preferably, the microalgae is selected from the diatom micro-algae species *Phaeodactylum tricornutum* and *Thalassiosira pseudonana*, and the 10 Chromalveolata micro-algae species *Nannochloropsis*, and more preferably *Nannochloropsis gaditana*, *Nannochloropsis oceanica*, *Nannochloropsis salina*.

Sterol inhibitors consist of molecules that have an effect on any protein activity in the biosynthesis of sterols, a pathway that starts with the biosynthesis of HMG-CoA reductase, followed by the biosynthesis of mevalonic acid, epoxysqualene and then all steroid structures 15 deriving from epoxysqualene (see **Figure 1**). The identification of compounds which inhibit sterol metabolism, preferably with at least a decrease of 20% of total sterol content per cell, can be achieved simply by colorimetric or fluorometric dosage methods such as that commercialized by CellBioLabs (Total Sterol Assay Kit, Colorimetric method, reference STA-384 or Fluorometric method, reference STA-390), based on a treatment by cholesterol 20 oxidase/esterase, which has proved to be efficient on detecting plant sterols (D. Kritchevsky and S. A. Tepper, Clinical Chemistry, Vol. 25, No. 8, 1464-1465 (1979)), or also according to methods such as those exemplified in the applications WO 2010/046385 and WO 97/03202.

According to an embodiment of the invention, the inhibitor of sterol metabolism is a compound of formula (I) or a salt thereof:



wherein:

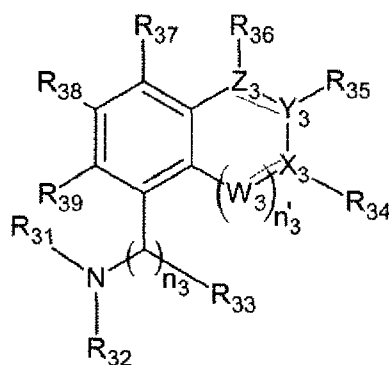
- R_{41} and R_{42} , identical or different, represent a hydrogen atom, alkyl, alkenyl, alkynyl, or hydroxyl, $-COR_{4a}$ or $-COOR_{4a}$ group, in which R_{4a} represents a hydrogen atom, linear or branched alkyl, aryl, heteroaryl group, optionally substituted with one or more groups independently selected from alkyl or cycloalkyl groups, preferably C_4 - C_6 cycloalkyl groups, or R_{41} and R_{42} form together an oxygen atom attached by a double bond;

- R_{43} represents a hydrogen atom, or an alkyl group, preferably C_1 - C_3 alkyl group; and

- R_{44} , R_{45} and R_{46} , identical or different, represent a hydrogen atom, alkyl, alkoxy, hydroxyl group, or an oxygen atom attached by a double bond, said alkyl group being optionally substituted with one or more halogen atoms, and including optionally in its chain one or more sulfoxide functions.

Advantageously, R_{41} and R_{42} , identical or different, represent a hydrogen atom, a nitrile, hydroxyl, C_1 - C_2 alkyl or $-COOR_{4a}$ group in which R_{4a} is in C_1 - C_7 and is optionally substituted by a C_4 - C_6 cycloalkyl group, or R_{41} and R_{42} form together an oxygen atom attached by a double bond.

According to another embodiment of the invention, the inhibitor of sterol metabolism is a compound of formula (II) or a salt thereof:



(II)

wherein:

- W_3 , X_3 , Y_3 and Z_3 represent carbon, sulphur, nitrogen or oxygen atom, and preferably W_3 , X_3 , Y_3 and Z_3 represent carbon atoms;

- n_3 and $n_{3'}$, independently, are integer equal to 0 or 1, and preferably n_3 and $n_{3'}$ are equal to 1;

- R_{31} and R_{32} , identical or different, represent a hydrogen atom, linear or branched alkyl, alkenyl, alkynyl, alkylalkenyl, alkynylalkenyl, cycloalkyl, alkylaryl, arylalkyl, and preferably a benzyl group, arylalkenyl, arylalkynyl, heteroalkyl, heteroaryl groups, or form together a cycloalkyl group comprising 5 to 6 carbon atoms, one or two carbon atoms of said cycloalkyl

group being possibly replaced by one or two heteroatoms, preferably nitrogen atoms, or one of R_{31} or R_{32} form together with R_{39} a cycloalkyl group comprising 5 to 6 carbon atoms, one or two carbon atoms of said cycloalkyl group being possibly replaced by one or two heteroatoms, preferably oxygen atoms, said R_{31} or R_{32} being optionally substituted with one or more groups independently selected from linear or branched alkyl, cycloalkyl such as



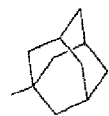
, alkynyl, said alkynyl group being preferably a C_5 - C_{12} branched alkynyl group, arylalkyl, aryl, heteroaryl, hydroxyl, halogen, nitro, $-COR_{3a}$ or $-NR_{3a}R_{3b}$ group, in which R_{3a} and R_{3b} , identical or different, represent a hydrogen atom or a linear or branched alkyl chain;

- R_{33} represents a hydrogen atom, a linear or branched alkyl chain such as a C_1 - C_3 alkyl group, or a nitrile group, and preferably R_{33} represents a hydrogen atom;

- R_{34} , R_{35} , R_{36} , R_{37} , R_{38} and R_{39} , identical or different, represent hydrogen or halogen atoms, or hydroxyl groups, and preferably R_{34} , R_{35} , R_{36} , R_{37} , R_{38} and R_{39} are hydrogen atoms.

The dotted lines of formula (II) represent single or double bonds. Specifically, said W_3 - X_3 bond or Y_3 - Z_3 bond is single bond respectively when one of W_3 or X_3 of the W_3 - X_3 bond, or one of Y_3 or Z_3 of the Y_3 - Z_3 bond, is sulphur or oxygen. Said W_3 - X_3 bond or Y_3 - Z_3 bond is double bond respectively when W_3 and X_3 , or Y_3 and Z_3 are carbon or nitrogen.

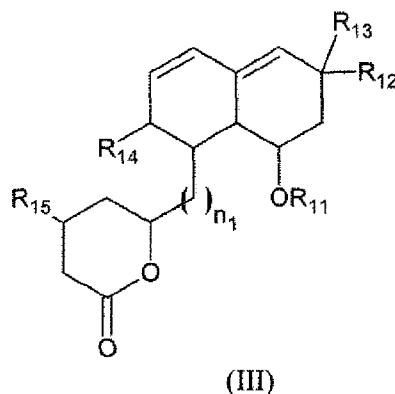
According to a preferred embodiment, R_{31} and R_{32} , identical or different, represent a hydrogen atom, linear or branched alkyl, alkenyl, alkynyl, alkynylalkenyl, cycloalkyl, alkylaryl, arylalkyl, and preferably a benzyl group, arylalkenyl, arylalkynyl, heteroalkyl, heteroaryl groups, or form together a cycloalkyl group comprising 5 to 6 carbon atoms, one or two carbon atoms of said cycloalkyl group being possibly replaced by one or two heteroatoms, preferably nitrogen atoms, or one of R_{31} or R_{32} form together with R_{39} a cycloalkyl group comprising 5 to 6 carbon atoms, one or two carbon atoms of said cycloalkyl group being possibly replaced by one or two heteroatoms, preferably oxygen atoms, said R_{31} or R_{32} being optionally substituted with one or more groups independently selected from



linear or branched alkyl, cycloalkyl such as , alkynyl, said alkynyl group being preferably a C_5 - C_{12} branched alkynyl group, arylalkyl, aryl, heteroaryl, hydroxyl, halogen, nitro, $-COR_{3a}$ or $-NR_{3a}R_{3b}$ group, in which R_{3a} and R_{3b} , identical or different, represent a hydrogen atom or a linear or branched alkyl chain.

According to a more preferred embodiment, R_{31} and R_{32} , identical or different, represent C_1 - C_6 linear or branched alkyl chains, or an arylalkyl group, optionally substituted with one or more groups independently selected from linear or branched alkyl. Advantageously, R_{31} represents a C_1 - C_6 linear or branched alkyl chain, and R_{32} a benzyl group substituted with a C_1 - C_6 linear or branched alkyl chain, or an alkenyl group substituted with a linear or branched alkynyl group, such as a $-(CH_2)_{n_3}-CH=CH-C\equiv C-C(CH_3)_3$ group in which n_3 ranges from 1 to 6.

According to another embodiment of the invention, the inhibitor of sterol metabolism is a compound of formula (III) or a salt thereof:



wherein:

- n_1 ranges from 1 to 12, and preferably $n_1 = 2$,
- R_{11} represents a hydrogen atom; a $-COR_{1a}$ group, in which R_{1a} is a group selected from a linear or branched alkyl chain, optionally substituted with one or more groups independently selected from hydroxyl, halogen, nitro, optionally substituted benzyl groups, or optionally substituted aryl groups such as phenyl groups, said aryl groups being eventually substituted with one or more groups independently selected from halogen atoms and methyl groups;
- R_{12} , R_{13} and R_{14} , identical or different, represent a hydrogen atom; a linear or branched alkyl chain; a hydroxyl group; a $-CH_2OH$ group; a $-COOR_{1b}$ group, in which R_{1b} represents a hydrogen atom, or a linear or branched alkyl chain; a $-OSiR_{1c}R_{1d}R_{1e}$ group, in which R_{1c} , R_{1d} and R_{1e} , identical or different, represent a hydrogen atom, or a linear or branched alkyl chain; or R_{12} and R_{13} are fused together to form an exo methylene group;
- R_{15} represents a hydroxyl group; a $-OSiR_{1c}R_{1d}R_{1e}$ group as defined above; a $-COOR_{1f}$ group, in which R_{1f} represents a hydrogen atom, or a linear or branched alkyl chain; a $-OCOR_{1g}$ group, in which R_{1g} represents a linear or branched alkyl chain, preferably a C_1 - C_3 alkyl chain, and more preferably a C_1 alkyl group; or R_{15} is a carbon forming an ethylenic unsaturation with the tetrahydropyranone ring.

According to a preferred embodiment, R_{11} is a $-\text{COR}_{1a}$ group, in which R_{1a} is a linear or branched alkyl chain, and preferably R_{11} is a $-\text{COCH}(\text{CH}_3)\text{C}_2\text{H}_5$ or $-\text{COC}(\text{CH}_3)_2\text{C}_2\text{H}_5$ group.

Advantageously, R_{14} represent a $\text{C}_1\text{-C}_6$ alkyl chain, preferably a $-\text{CH}_3$ group, and both
5 R_{12} and R_{13} represent hydrogen atoms. Alternatively, R_{12} and R_{14} may represent a $\text{C}_1\text{-C}_6$ alkyl chain, preferably a $-\text{CH}_3$ group, and R_{13} a hydrogen atom.

According to another preferred embodiment, $n_1 = 2$, and R_{15} represents a hydroxyl group.

According a preferred embodiment of the invention, the inhibitor of sterol metabolism
10 is selected from Ethinylestradiol, Mevastatin, Simvastatin, Butenafine, Terbinafine, Estrone. The most preferred inhibitors of sterol metabolism of formula (I) are Ethinylestradiol and Estrone. The most preferred inhibitor of sterol metabolism of formula (II) is Butenafine. The most preferred inhibitors of sterol metabolism of formula (III) are Mevastatin and Simvastatin.

15 The inhibitors of sterol metabolism of the invention are all acting on the "mevalonate" pathway, and not on the "non-mevalonate" pathway of synthesis of sterols (see **Figure 1**).

More specifically:

- the inhibitors of sterol metabolism of formula (I) are acting as steroid structural analogs interacting with protein involved in sterol metabolism including Estrone (Merola and
20 Arnold, Science, Vol. 144, 301-302 (1964)) and Ethinylestradiol (Koopen *et al.*, Journal of Lipid Research, Vol. 40, 1999),

- the inhibitors of sterol metabolism of formula (II) are acting as squalene epoxidase inhibitors (Belter *et al.*, Biol. Chem., Vol. 392, 1053-1075 (2011)), and

- the inhibitors of sterol metabolism of formula (III) are acting as HMG-CoA
25 reductase inhibitors (Liu *et al.*, Mol. Biol. Rep. (2010) 37:1391-1395).

Another subject-matter of the invention is a method for producing fatty acids comprising a triggering of triacylglycerols accumulation step in microalgae as defined according to the invention, followed by an extraction step of the triacylglycerols accumulated in the microalgae.

30 The invention also relates to a method for producing biofuels comprising the following steps:

(i) a triggering of triacylglycerols accumulation step in microalgae as defined according to the invention, followed by

(ii) an extraction step of the triacylglycerols accumulated in microalgae during step (i), and

(iii) a trans-esterification step of the triacylglycerols recovered during step (ii), for example as described by Zhang *et al.*, Bioresource Technology 147 (2013) 59-64.

5 The invention also concerns a method for producing pharmaceutical or cosmetic compositions comprising the following steps:

(i') a triggering of triacylglycerols accumulation step in microalgae as defined according to the invention, followed by

(ii') an extraction step of the triacylglycerols accumulated in microalgae during step (i'), and
10

(iii') a step of adding at least one pharmaceutically or cosmetically acceptable excipient to the triacylglycerols recovered during step (ii').

The invention also relates to a method for producing human food and animal feed supplements comprising the following steps:

15 (i'') a triggering of triacylglycerols accumulation step in microalgae as defined according to the invention, followed by

(ii'') an extraction step of the triacylglycerols accumulated in microalgae during step (i''), and

(iii'') a step of adding at least one food additive to the triacylglycerols recovered
20 during step (ii'').

The methods of the invention may comprise one or more extraction steps after the triggering of triacylglycerols accumulation step in microalgae. The extraction step may be implemented using solvents or another extraction method well known from the skilled artisan.

Another subject-matter of the invention relates to the use of an inhibitor of sterol
25 metabolism to accumulate triglycerides in microorganism, preferably in microalgae, more preferably in microalgae of the diatom phylum, and still more preferably in the diatom microalgae species *Phaeodactylum tricornutum*.

Advantageously, the invention concerns the use of an inhibitor of sterol metabolism selected from the compounds of formula (I), (II) and (III), such as Ethinylestradiol,
30 Mevastatin, Simvastatin, Butenafine, Terbinafine, Estrone, to accumulate triglycerides in microorganism, preferably in microalgae, more preferably in microalgae of the diatom phylum, and still more preferably in the diatom microalgae species *Phaeodactylum tricornutum*. The invention also concerns the use of combination of inhibitors of sterol metabolism selected from the compounds of formula (I), (II) and (III), such as

Ethinylestradiol, Mevastatin, Simvastatin, Butenafine, Terbinafine, Estrone, as well as their combination with other methods known to enhance the accumulation of TAG in microalgae, in particular a shortage of nutrient, and more preferably a shortage of nitrogen.

In addition to the above provisions, the invention also comprises other provisions which will emerge from the remainder of the description which follows, and also to the appended drawings in which:

- **Figure 1** gives a schematic view of the sterol biosynthetic pathway via mevalonic acid, and represents the action of Mevastatin and Simvastatin (Liu *et al.*, Mol. Biol. Rep. (2010) 37:1391-1395), Estrone (Merola and Arnold, Science, Vol. 144, 301-302 (1964), Butenafine and Terbinafine (Belter *et al.*, Biol. Chem., Vol. 392, 1053-1075 (2011)),

- **Figure 2** represents pictures of a *Phaeodactylum* cell visualized by confocal microscopy after a 72h cultivation in Nitrogen-rich N(+) or in Nitrogen-starved N(-) medium. On the left side (A and C), cells are shown in phase contrast ("phase"). On the right side (B and D), cells are shown after excitation of Nile red at 488 nm and emission at 519 nm,

- **Figure 3 a-h** illustrates the dose response for Ethinylestradiol, Mevastatin, Simvastatin and Estrone, and

- **Figure 4** illustrates the dose response for Ethinylestradiol, Mevastatin and Simvastatin with an evaluation of the TAG content by staining with Nile Red and an evaluation of cells by counting in an aliquote fraction using a Malassez cell,

- **Figure 5** shows the effect of Butenafine on Nile Red accumulation in *Nannochloropsis gaditana* grown respectively in ESAW 1N1P media and ESAW 10N10P media. Nile Red Fluorescence was normalized by calculating the relative fluorescence units per million cells, and

- **Figure 6** shows the effect of Ethinylestradiol on Nile Red accumulation in *Nannochloropsis gaditana* grown respectively in ESAW 1N1P media and ESAW 10N10P media. Nile Red Fluorescence was normalized by calculating the relative fluorescence units per million cells.

EXAMPLES:**1) Materials & Methods****5 1) 1- *Phaeodactylum tricornutum* strain and growth conditions**

Phaeodactylum tricornutum (Pt1) Bohlin Strain 8.6 CCMP2561 (Culture Collection of Marine Phytoplankton, now known as NCMA: National Center for Marine Algae and Microbiota) was used in experiments.

Pt1 was grown at 20°C in 250 mL flask using “enriched artificial seawater” (ESAW) medium, prepared following the recommendations of the Canadian Center for the Culture of Microorganisms.

To prepare the ESAW medium, four separated solutions are prepared, two solutions of salts (solutions 1 and 2), one solution of nutrients, and one solution of vitamins. Salts are added in order to distilled deionized water (DDW). When the salts in solutions 1 and 2 are completely dissolved, the solutions 1 and 2 are mixed together. The total volume is diluted with DDW.

Table 3: Compositions of the ESAW salts solutions 1 and 2

Solution 1: Anhydrous salts	Molecular weight (g.mol ⁻¹)	Amount to weight (g/L solution)	Concentration (mM)
NaCl	58.44	20.756	362.7
Na ₂ SO ₄	142.04	3.477	25.0
KCl	74.56	0.587	8.03
NaHCO ₃	84	0.17	2.067
KBr	119.01	0.0845	0.725
H ₃ BO ₃	61.83	0.022	0.372
NaF	41.99	0.0027	0.0657
Solution 2: Hydrated salts			
MgCl ₂ .6H ₂ O	203.33	9.395	47.18
CaCl ₂ .2H ₂ O	147.03	1.316	9.134
SrCl ₂ .6H ₂ O	266.64	0.0214	0.082

Table 4: Nutrient Enrichment Stocks

Solutions		Stock concentration (g.L ⁻¹)	Final concentration (μM)
1	NaNO ₃	46.67	549.1
2*	Na ₂ glycerophosphate	6.67	21.8
3	Na ₂ SiO ₃ .9H ₂ O	15.00	105.6
4**	Na ₂ EDTA.2H ₂ O	3.64	9.81
	Fe(NH ₄) ₂ (SO ₄) ₂ .6H ₂ O***	2.34	5.97
	FeCl ₃ .6H ₂ O	0.16	0.592
5	MnSO ₄ .4H ₂ O	0.54	2.42
	ZnSO ₄ .7H ₂ O	0.073	0.254
	CoSO ₄ .7H ₂ O	0.016	0.0569
	Na ₂ MoO ₄ .2H ₂ O	0.126	0.520
	Na ₂ EDTA.2H ₂ O	1.89	5.05
6	H ₃ BO ₃	3.80	61.46
7	NaSeO ₃	0.00173	0.001

* Na₂ glycerophosphate can be replaced with an equimolar stock of Na₂HPO₄.

** Na₂EDTA.2H₂O is added before the trace metals Fe(NH₄)₂(SO₄)₂.6H₂O and FeCl₃.6H₂O.

5 *** Fe(NH₄)₂(SO₄)₂.6H₂O can be replaced with an equimolar stock of FeCl₃.

Solution 5 is adjusted to pH = 6 with 2 g of Na₂CO₃.

Solution 4 can be heated to dissolve the iron.

Table 5: Vitamin Stocks

Vitamin Stock	Stock concentration (g.L ⁻¹)	Final concentration (mM)
Thiamine	0.1	2.97×10^{-1}
Vitamin B12	0.002	1.47×10^{-3}
Biotin	0.001	4.09×10^{-3}

10

To prepare the ESAW medium, the solutions are filtered through 0.45 μm membrane filter with a glass fiber prefilter. A flask is acid-washed in 10% HCl and rinsed in distilled water before first use. To 1 L of filtered salt solution, 1 mL of Nutrient Enrichment Stock solutions 1, 2, 4, 5, 6 and 7, 2 mL of Nutrient Enrichment Stock solution 3, and 2 mL of the Vitamin Stock are added (Tables 4 and 5). To reduce precipitation during autoclaving, 1.44 mL of 1N HCl and 0.12g of sodium bicarbonate are added. The obtained ESAW medium is then sterilized by autoclaving.

15

Cells were grown on a 12:12 light (450 μEinstein - 1 sec⁻¹) / dark cycle (an Einstein defined the energy in one mole (6.022×10^{23}) of photons). Cells were sub-cultured every

week by inoculate fresh media with 1/5 of previous culture. Nitrogen-rich N(+) medium contained no source of nitrogen. Nitrogen-starved N(-), medium contained 0.05 g/L NaNO₃. To monitor cell growth, a genetically modified strain containing a Histone H4 protein fused to the yellow fluorescent protein was used (Siaut *et al.*, Gene 406 (2007) 23-35).

5 1) 2- Principle of Nile Red staining of oil droplets

Accumulation of oil droplets can be monitored by Nile Red (Sigma Aldrich) fluorescent staining (Excitation wavelength at 485 nm; emission at 525 nm) as described by Ren *et al.* (Biotechnology for Biofuels 2013, 6:143). Cells were diluted and adjusted to a cell density that was linearly correlated with Nile Red fluorescence. Nile Red solution (40 µL of
10 2.5 µg.mL⁻¹ stock concentration, in 100% DMSO) was added to 160 µL cell suspension. Specific fluorescence was determined by dividing Nile Red fluorescence intensity by the number of cells. Oil bodies stained with Nile Red were then visualized using a Zeiss AxioScope.A1 microscope (FITC filter; Excitation wavelength at 488 nm; **emission** at 519 nm).

15 Lipid droplets can be visualized. In **Figure 2**, a *Phaeodactylum* cell was visualized by confocal microscopy after a 72h cultivation in Nitrogen-rich N(+) medium or in Nitrogen-starved N(-) medium. On the left side, cells are shown in phase contrast ("phase"). On the right side, cells are shown after excitation of Nile red at 488 nm and emission at 519 nm. Lipid droplets can be clearly visualized.

20 This principle was use to measure the presence of oil in *Phaeodactylum tricornutum* simply by using a spectrofluorometer (in these conditions, to lower the detection of other fluorophores within the cell, such as chlorophylls, excitation was at 530 nm and emission at 580 nm).

1) 3- Alternative method for oil level detection

25 Alternatively, oil is extracted using solvents or another extraction method, separated and purified by thin layer chromatography and methanolized to produce fatty acid methyl esters and quantified by gas chromatography coupled to a ionization flame detector or a mass spectrometer.

30 TAG were extracted from 200 mg of freeze-dried *Phaeodactylum tricornutum* cells in order to prevent lipid degradation. Briefly, cells were frozen in liquid nitrogen immediately after harvest. The freeze-dried cell pellet was resuspended in 4 mL of boiling ethanol for 5 minutes followed by the addition of 2 mL of methanol and 8 mL of chloroform at room temperature. The mixture was then saturated with argon and stirred for 1h at room temperature. After filtration through glass wool, cell remains were rinsed with 3 mL of

chloroform/methanol (2:1, v/v). In order to initiate biphasic formation, 5 mL of NaCl 1% was then added to the filtrate. The chloroform phase was dried under argon before resolubilization of the lipid extract in pure chloroform. To isolate TAG, lipids were run on silica gel thin layer chromatography (TLC) plates (Merck) with hexane/diethylether/acetic acid (70:30:1, v/v). Lipids were then visualized under UV light after pulverization of 8-anilino-1-naphthalenesulfonic acid at 2% in methanol. They were then scraped off from the TLC plates for further analyses. For acyl profiling and quantification of TAG, fatty acids were methylated using 3 mL of 2.5% H₂SO₄ in methanol during 1h at 100°C (including standard amounts of 21:0). The reaction was stopped by the addition of 3 mL of water and 3 mL of hexane. The hexane phase was analyzed by gas liquid chromatography (Perkin Elmer) on a BPX70 (SGE) column. Methylated fatty acids were identified by comparison of their retention times with those of standards and quantified by surface peak method using 21:0 for calibration. Extraction and quantification were done at least 3 times.

1) 4- Principle of cell normalization

The number of cells in a sample can be evaluated using a fluorescent reporter, like the strain by Siaut *et al.* (Gene 406 (2007) 23-35) containing a genetic construction with Histone H4 protein fused to the Yellow Fluorescent Protein (YFP) (Figure 5A of Siaut *et al.*, Gene 406 (2007) 23-35).

For cell counting, we can either use this strain called "ptYFP" and measure the fluorescence emitted by the YFP at 530 nm after excitation at 515 nm, or use any strain and estimate cell numbers by counting with a Malassez grid (supplier: Mareinfeld).

1) 5- Incubation of *Phaeodactylum tricornutum* with inhibitors of the sterol metabolism and detection of oil accumulation triggered by the treatment

On the first day, we prepared 48 well plates by adding 4 mm glass beads sterilized with Ultra-Violet exposure in each well.

We prepared fresh suspensions of microalgae in exponential growth phase. For cell normalization based on YFP fluorescence, cells of *Phaeodactylum tricornutum* containing a YFP reporter (ptYFP) cultured in N(+) ESAW medium were centrifuged at 3,500 rpm, 5 min. For cell normalization based on counting using a Malassez grid, cells of the Pt1 strain of *Phaeodactylum tricornutum* cultured in N(+) ESAW medium were centrifuged at 3,500 rpm, 5 min. The supernatant was discarded and the pellet suspended in N(-) ESAW. The microalgae were then centrifuged at 3,500 rpm, 5 min. The supernatant was discarded and the pellet suspended in N(-) ESAW. Cells were then diluted to 1x10⁶ cells/mL in N(-) ESAW. Samples were then separated into two batches. One was supplemented with 1 µL/mL of 46.7

g/L NaNO₃ stock to obtain a suspension of cells in N(+) ESAW medium. Another was left without NaNO₃ to obtain a N(-) ESAW culture as a control for high lipid accumulation. In a 48-well clear NUNC plate, 450 µL/well of 1x10⁶ cells/mL were dispensed.

For a dose-response analysis, each well of the 48-well plate was then subjected to an appropriate incubation with 0, 1, 10 or 100 µM of inhibitor of sterol metabolism using 50 µL of the following: 50 µL of a 10 time concentrated solution of inhibitor of sterol metabolism (5% DMSO:95% N(+) ESAW) or 50 µL of Nitrogen-rich medium without any inhibitor of sterol metabolism (5% DMSO:95% N(+) ESAW) or Nitrogen-starved medium without any inhibitor of sterol metabolism (5% DMSO:95% N(-) ESAW) as a positive control.

For an analysis of the effect of a single dose, an incubation was performed with 0, and a chosen concentration of inhibitor of sterol metabolism (50 µM).

In all cases, the edge of the plate was sealed using a parafilm. Plates were incubated for 48h in an incubator with top lighting, 20°C, 100 rpm, 12h/12h light/dark.

After an incubation of 48 hours, fluorescence was measured at the following excitation/emission wavelengths, 530/580 nm (to evaluate a baseline fluorescence prior Nile Red addition) and 515/530 nm (to evaluate YFP fluorescence). Following this first measure, 40 µL of Nile Red (2.5 µg/mL stock concentration, in 100% DMSO) are added. Plates are mixed and incubated 20 minutes at room temperature, protected from light. Nile Red fluorescence is then measured using a spectrofluorometer (excitation 530 nm/emission 580 nm).

1) 6- Incubation of *Nannochloropsis gaditana* with inhibitors of the sterol metabolism and detection of oil accumulation triggered by the treatment

Experiments were performed in two different conditions of *Nannochloropsis gaditana*: cells were either cultured in ESAW containing 47 mg.L⁻¹ NaNO₃ and 3 mg.L⁻¹ NaH₂PO₄ (medium 1N1P), or 470 mg/L NaNO₃ and 30 mg.L⁻¹ NaH₂PO₄ (medium 10N10P).

Cells in an exponential growth phase were collected via centrifugation at 3500 rpm for 10 minutes. The supernatant was discarded and the cells were resuspended in the same volume of ESAW medium (either 1N1P or 10N10P). The cultures were centrifuged again at 3500 rpm, for 10 minutes, and the supernatant was discarded. The pellet was resuspended in ESAW (either 1N1P or 10N10P) to obtain a concentration of 2x10⁶ cells/mL. Cell counts were performed using a Malassez counting chamber, allowing 10 minutes for the cells to settle before counting.

Twenty milliliters of 2x10⁶ cells/mL of *Nannochloropsis gaditana* in ESAW (10N10P) and ESAW (1N1P) were dispensed into sterile glass conical flasks. Stocks of

inhibitor of sterol metabolism were prepared in DMSO. Inhibitors of sterol metabolism were added to the 20 mL *Nannochloropsis gaditana* samples at final concentrations of 10 μ M, 30 μ M, or 100 μ M. The maximum final concentration of DMSO in the samples was 1% (v/v). All cultures were incubated for seven days at 100 rpm, 12h/12h light/dark cycle, 50 μ E.m⁻².s⁻¹, 20°C.

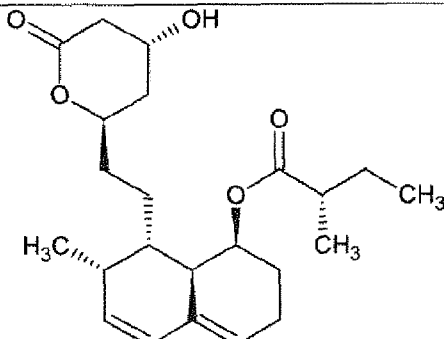
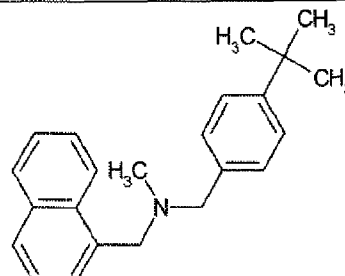
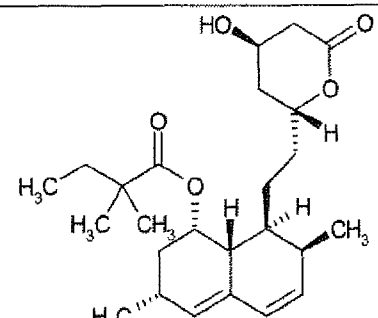
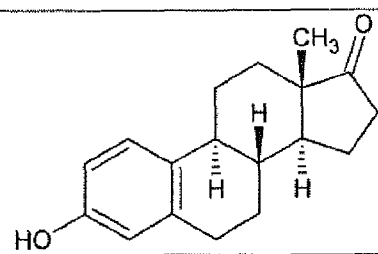
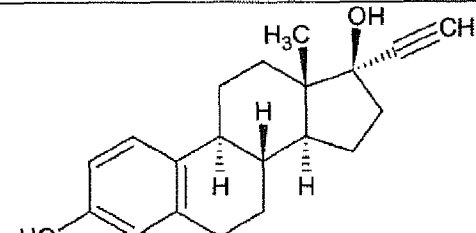
Each day, an aliquot was taken from each flask in order to perform a Nile Red stain and cell counts. 160 μ L per sample was added to black 96 well plates, and allowed to settle for 10 minutes. In order to detect any background noise, fluorescence was measured at excitation and emission of 530 nm and 580 nm, respectively. 40 μ L of 2.5 μ g.mL⁻¹ Nile Red in DMSO was added to each well, and mixed thoroughly. After 20 minutes of incubation, Nile Red fluorescence was measured at excitation and emission of 530 nm and 580 nm, respectively.

Nile Red Fluorescence was normalized by calculating the relative fluorescence units per million cells. Results were expressed as a percentage of Nile Red fluorescence of *Nannochloropsis gaditana* cultured in complete medium (either ESAW (10N10P) or ESAW (1N1P)).

1) 7- Inhibitors of sterol metabolism

Inhibitors of sterol metabolism were obtained from the Prestwick library for their ability to trigger the accumulation of lipid droplets within the cells of *Phaeodactylum tricornutum*, and then purchased from Sigma-Aldrich.

Table 6: Inhibitors of sterol metabolism selected from the Prestwick library

Chemical name	Structure	Molecular Formula
Mevastatin		$C_{23}H_{34}O_5$
Butenafine		$C_{23}H_{27}N$
Simvastatin		$C_{25}H_{38}O_5$
Estrone		$C_{18}H_{22}O_2$
Ethinylestradiol		$C_{20}H_{24}O_2$

2) Results

Phaeodactylum tricornutum was incubated for 48h in presence of 10 μ M of Mevastatin, Butenafine, Simvastatin, Estrone, Ethinylestradiol and Terbinafine.

5 In all cases the presence of oil per cell increased by a factor of at least 1.5, based on Nile Red staining.

Figure 3 a-h illustrates the dose response for Ethinylestradiol, Mevastatin, Simvastatin and Estrone with an evaluation of the TAG content by staining with Nile Red, and an evaluation of cells by monitoring YFP fluorescence from an expressed Histone H4
10 reporter gene. On the left, **Figure 3 a-h** shows the Nile Red levels in percent of untreated cells and the number of cells estimated by the YFP fluorescence expressed in percent of untreated cells. The right panels show the increase of oil content per cell, by the ratio of Nile Red fluorescence/YFP fluorescence, expressed in percent of untreated cells. The oil content per cell increases with drug concentration and consequently level of sterol metabolism
15 inhibition and ranges from 120 to 400 % when compared to untreated cells.

Figure 4 illustrates the dose response for Ethinylestradiol (A), Mevastatin (B) and Simvastatin (C) with an evaluation of the TAG content by staining with Nile Red and an evaluation of cells by counting in an aliquote fraction using a Malassez cell. In histograms of **Figure 4**, the white bars indicate the evaluation of cell numbers in percent of untreated cells,
20 and the black bars indicate the Nile Red per 10^6 cell, in percent of untreated cells. The oil content per cell, and consequently level of sterol metabolism inhibition, increases with incubation of 50 μ M of inhibitor, and ranges from 120 to 350% when compared to untreated cells.

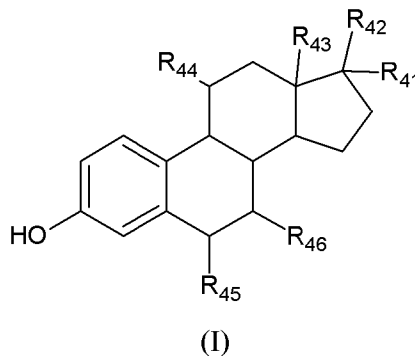
25 *Nannochloropsis gaditana* was incubated in presence of Butenafine and Ethinylestradiol.

Figures 5 and 6 illustrate the effect of Butenafine and Ethinylestradiol on Nile Red accumulation in *Nannochloropsis gaditana* grown respectively in ESAW 1N1P media and ESAW 10N10P media. Nile Red Fluorescence was normalized by calculating the relative
30 fluorescence units per million cells.

Both Butenafine and Ethinylestradiol trigger the accumulation of oil in *Nannochloropsis gaditana*, in different media and with a time course that can be observed at least for 7 days.

In some aspects, embodiments of the present invention as described herein include the following items:

1. A method for triggering triacylglycerols accumulation in microalgae by inhibiting the sterol metabolism, by incubating the microalgae with an inhibitor of sterol metabolism,
 5 metabolism,
 said inhibitor of sterol metabolism being a compound of one of the following formulae or a salt thereof:

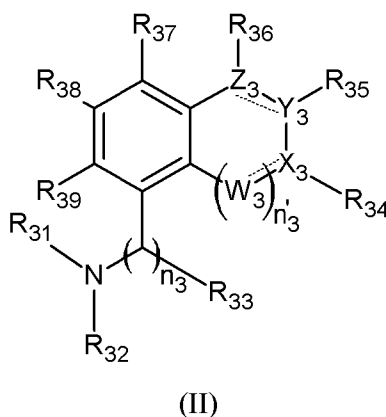


10 wherein:

- R_{41} and R_{42} , identical or different, represent a hydrogen atom, alkyl, alkenyl, alkynyl, or hydroxyl, $-COR_{4a}$ or $-COOR_{4a}$ group, in which R_{4a} represents a hydrogen atom, a linear or branched alkyl, aryl, heteroaryl group, optionally substituted with one or more groups independently selected from alkyl and cycloalkyl groups, or R_{41} and R_{42} form together an
 15 oxygen atom attached by a double bond;

- R_{43} represents a hydrogen atom, or an alkyl group; and

- R_{44} , R_{45} and R_{46} , identical or different, represent a hydrogen atom, an alkyl, alkoxy, hydroxyl group, or an oxygen atom attached by a double bond, said alkyl group being optionally substituted with one or more halogen atoms, and including optionally in its chain one or more
 20 sulfoxide functions;



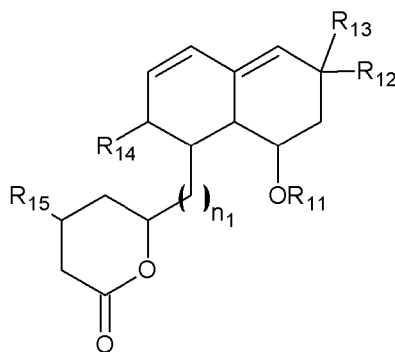
wherein:

- W_3 , X_3 , Y_3 and Z_3 represent carbon, sulphur, nitrogen or oxygen atom;
- n_3 and n_3' , independently, are integer equal to 0, which corresponds to a single bond for the residue into brackets, or 1;

- 5 - R_{31} and R_{32} , identical or different, represent a hydrogen atom, linear or branched alkyl, alkenyl, alkynyl, alkylalkenyl, alkynylalkenyl, cycloalkyl, alkylaryl, arylalkyl, arylalkenyl, arylalkynyl, heteroalkyl, heteroaryl groups, or form together a cycloalkyl group comprising 5 to 6 carbon atoms, or form together a cycloalkyl group comprising 5 to 6 carbon atoms in which one or two carbon atoms of said cycloalkyl group is replaced by one or two heteroatoms, or one of R_{31} or R_{32} form together with R_{39} a cycloalkyl group comprising 5 to 6 carbon atoms, or one of R_{31} or R_{32} form together with R_{39} a cycloalkyl group comprising 5 to 6 carbon atoms in which one or two carbon atoms of said cycloalkyl group is replaced by one or two heteroatoms, said R_{31} or R_{32} being optionally substituted with one or more groups independently selected from linear or branched alkyl, cycloalkyl, alkynyl, arylalkyl, aryl, heteroaryl, hydroxyl, halogen, nitro, $-COR_{3a}$ and $-NR_{3a}R_{3b}$ group, in which R_{3a} and R_{3b} , identical or different, represent a hydrogen atom, or a linear or branched alkyl chain;

- R_{33} represents a hydrogen atom, a linear or branched alkyl chain, or a nitrile group;

- R_{34} , R_{35} , R_{36} , R_{37} , R_{38} and R_{39} , identical or different, represent hydrogen or halogen atoms, or hydroxyl groups; or



(III)

wherein:

- n_1 ranges from 1 to 12,

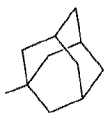
- 25 - R_{11} represents a hydrogen atom; a $-COR_{1a}$ group, in which R_{1a} is a group selected from a linear or branched alkyl chain, optionally substituted with one or more groups independently selected from hydroxyl, halogen, nitro, optionally substituted benzyl groups, and optionally substituted aryl groups, said aryl groups being eventually substituted with one or more groups independently selected from halogen atoms and methyl groups;

- R₁₂, R₁₃ and R₁₄, identical or different, represent a hydrogen atom; a linear or branched alkyl chain; a hydroxyl group; a -CH₂OH group; a -COOR_{1b} group, in which R_{1b} represents a hydrogen atom, or a linear or branched alkyl chain; a -OSiR_{1c}R_{1d}R_{1e} group, in which R_{1c}, R_{1d} and R_{1e}, identical or different, represent a hydrogen atom, or a linear or branched alkyl chain;
 5 or R₁₂ and R₁₃ form together an exo methylene group;

- R₁₅ represents a hydroxyl; a -OSiR_{1c}R_{1d}R_{1e} group; a -COOR_{1f} group, in which R_{1f} represents a hydrogen atom, or a linear or branched alkyl chain; a -OCOR_{1g} group, in which R_{1g} represents a linear or branched alkyl chain; or R₁₅ is a carbon forming an ethylenic unsaturation with the tetrahydropyranone ring.

10 2. The method according to Item 1, wherein n₃ and n_{3'} are equal to 1.

3. The method according to Item 1 or 2, wherein said R₃₁ or R₃₂ are optionally substituted with one or more groups independently selected from linear or branched alkyl,



, alkynyl, arylalkyl, aryl, heteroaryl, hydroxyl, halogen, nitro, -COR_{3a} and -NR_{3a}R_{3b} group, in which R_{3a} and R_{3b}, identical or different, represent a hydrogen atom, or a linear or
 15 branched alkyl chain.

4. The method according to any one of Items 1 to 3, wherein R_{1a} is a group selected from a linear or branched alkyl chain, optionally substituted with one or more groups independently selected from hydroxyl, halogen, nitro, optionally substituted benzyl groups, and optionally substituted phenyl groups, said phenyl groups being eventually substituted with one
 20 or more groups independently selected from halogen atoms and methyl groups.

5. The method according to any one of Items 1 to 4, wherein the incubation step is implemented in a nitrogen medium.

6. The method according to any one of Items 1 to 5, wherein the microalgae is selected from microalgae of the diatom phylum, the Chromalveolata phylum, and the
 25 Archaeplastidae phylum.

7. The method according to Item 6, wherein the microalgae is selected from the diatom micro-algae species *Phaeodactylum tricornutum* and *Thalassiosira pseudonana*, the Chromalveolata micro-algae species *Nannochloropsis*, and the Archaeplastidae micro-algae species *Chlamydomonas*, *Ostreococcus*, and *Chlorella*.

30 8. The method according to Item 7, wherein the microalgae is selected from the diatom micro-algae species *Nannochloropsis gaditana*, *Nannochloropsis oceanica*, and *Nannochloropsis salina*.

9. The method according to any one of Items 1 to 8, wherein the inhibitor of sterol metabolism is selected from Ethinylestradiol, Estrone, Butenafine, Mevastatin, Simvastatin, and Terbinafine.

10. A method for producing fatty acids comprising a triggering of triacylglycerols accumulation step in microalgae as defined in any one of Items 1 to 9, followed by an extraction step of the triacylglycerols accumulated in the microalgae to yield fatty acids in the form of triacylglycerols.

11. A method for producing biofuels comprising the following steps:

- (i) a triggering of triacylglycerols accumulation step in microalgae as defined in any one of Items 1 to 9, followed by
- (ii) an extraction step of the triacylglycerols accumulated in microalgae during step (i), and
- (iii) a trans-esterification step of the triacylglycerols recovered during step (ii) to obtain biofuels.

12. A method for producing pharmaceutical or cosmetic compositions comprising the following steps:

- (i') a triggering of triacylglycerols accumulation step in microalgae as defined in any one of Items 1 to 9, followed by
- (ii') an extraction step of the triacylglycerols accumulated in microalgae during step (i'), and
- (iii') a step of adding at least one pharmaceutically or cosmetically acceptable excipient to the triacylglycerols recovered during step (ii') to obtain pharmaceutical or cosmetic compositions.

13. A method for producing food supplements comprising the following steps:

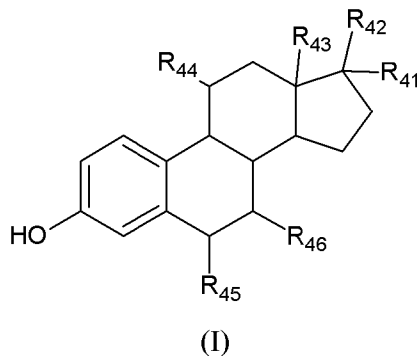
- (i'') a triggering of triacylglycerols accumulation step in microalgae as defined in any one of Items 1 to 9, followed by
- (ii'') an extraction step of the triacylglycerols accumulated in microalgae during step (i''), and
- (iii'') a step of adding at least one food additive to the triacylglycerols recovered during step (ii'') to obtain food supplements.

14. Use of an inhibitor of sterol metabolism chosen from the compounds of formula (I), (II) and (III), as defined in any one of items 1 to 4, to accumulate triglycerides in microalgae.

15. The use according to Item 14, wherein the inhibitor of sterol metabolism is chosen from Ethinylestradiol, Estrone, Butenafine, Mevastatin, Simvastatin, Terbinafine, or combination thereof.

CLAIMS

1. A method for triggering triacylglycerols accumulation in microalgae by inhibiting the sterol metabolism, by incubating the microalgae with an inhibitor of sterol metabolism,
 5 metabolism,
 said inhibitor of sterol metabolism being a compound of one of the following formulae or a salt thereof:

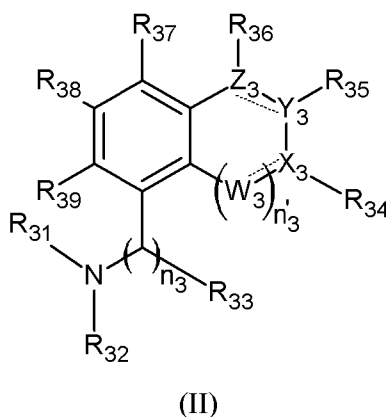


10 wherein:

- R_{41} and R_{42} , identical or different, represent a hydrogen atom, alkyl, alkenyl, alkynyl, or hydroxyl, $-COR_{4a}$ or $-COOR_{4a}$ group, in which R_{4a} represents a hydrogen atom, a linear or branched alkyl, aryl, heteroaryl group, optionally substituted with one or more groups independently selected from alkyl and cycloalkyl groups, or R_{41} and R_{42} form together an
 15 oxygen atom attached by a double bond;

- R_{43} represents a hydrogen atom, or an alkyl group; and

- R_{44} , R_{45} and R_{46} , identical or different, represent a hydrogen atom, an alkyl, alkoxy, hydroxyl group, or an oxygen atom attached by a double bond, said alkyl group being optionally substituted with one or more halogen atoms, and including optionally in its chain one or more
 20 sulfoxide functions;

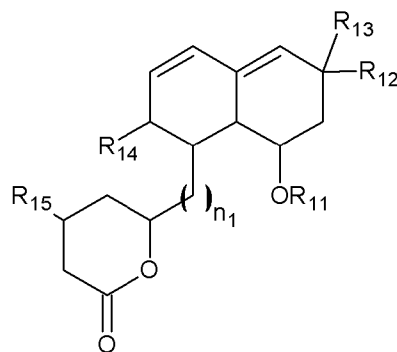


wherein:

- W_3 , X_3 , Y_3 and Z_3 represent carbon, sulphur, nitrogen or oxygen atom;
- n_3 and n_3' , independently, are integer equal to 0, which corresponds to a single bond for the residue into brackets, or 1;

- 5 - R_{31} and R_{32} , identical or different, represent a hydrogen atom, linear or branched alkyl, alkenyl, alkynyl, alkylalkenyl, alkynylalkenyl, cycloalkyl, alkylaryl, arylalkyl, arylalkenyl, arylalkynyl, heteroalkyl, heteroaryl groups, or form together a cycloalkyl group comprising 5 to 6 carbon atoms, or form together a cycloalkyl group comprising 5 to 6 carbon atoms in which one or two carbon atoms of said cycloalkyl group is replaced by one or two heteroatoms, or one of R_{31} or R_{32} form together with R_{39} a cycloalkyl group comprising 5 to 6 carbon atoms, or one of R_{31} or R_{32} form together with R_{39} a cycloalkyl group comprising 5 to 6 carbon atoms in which one or two carbon atoms of said cycloalkyl group is replaced by one or two heteroatoms, said R_{31} or R_{32} being optionally substituted with one or more groups independently selected from linear or branched alkyl, cycloalkyl, alkynyl, arylalkyl, aryl, heteroaryl, hydroxyl, halogen, nitro, $-COR_{3a}$ and $-NR_{3a}R_{3b}$ group, in which R_{3a} and R_{3b} , identical or different, represent a hydrogen atom, or a linear or branched alkyl chain;

- R_{33} represents a hydrogen atom, a linear or branched alkyl chain, or a nitrile group;
- R_{34} , R_{35} , R_{36} , R_{37} , R_{38} and R_{39} , identical or different, represent hydrogen or halogen atoms, or hydroxyl groups; or



(III)

wherein:

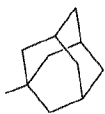
- n_1 ranges from 1 to 12,
- R_{11} represents a hydrogen atom; a $-COR_{1a}$ group, in which R_{1a} is a group selected from a linear or branched alkyl chain, optionally substituted with one or more groups independently selected from hydroxyl, halogen, nitro, optionally substituted benzyl groups, and optionally substituted aryl groups, said aryl groups being eventually substituted with one or more groups independently selected from halogen atoms and methyl groups;

- R₁₂, R₁₃ and R₁₄, identical or different, represent a hydrogen atom; a linear or branched alkyl chain; a hydroxyl group; a -CH₂OH group; a -COOR_{1b} group, in which R_{1b} represents a hydrogen atom, or a linear or branched alkyl chain; a -OSiR_{1c}R_{1d}R_{1e} group, in which R_{1c}, R_{1d} and R_{1e}, identical or different, represent a hydrogen atom, or a linear or branched alkyl chain;
 5 or R₁₂ and R₁₃ form together an exo methylene group;

- R₁₅ represents a hydroxyl; a -OSiR_{1c}R_{1d}R_{1e} group; a -COOR_{1f} group, in which R_{1f} represents a hydrogen atom, or a linear or branched alkyl chain; a -OCOR_{1g} group, in which R_{1g} represents a linear or branched alkyl chain; or R₁₅ is a carbon forming an ethylenic unsaturation with the tetrahydropyranone ring.

10 2. The method according to Claim 1, wherein n₃ and n_{3'} are equal to 1.

 3. The method according to Claim 1 or 2, wherein said R₃₁ or R₃₂ are optionally substituted with one or more groups independently selected from linear or branched alkyl,



, alkynyl, arylalkyl, aryl, heteroaryl, hydroxyl, halogen, nitro, -COR_{3a} and -NR_{3a}R_{3b} group, in which R_{3a} and R_{3b}, identical or different, represent a hydrogen atom, or a linear or
 15 branched alkyl chain.

 4. The method according to any one of Claims 1 to 3, wherein R_{1a} is a group selected from a linear or branched alkyl chain, optionally substituted with one or more groups independently selected from hydroxyl, halogen, nitro, optionally substituted benzyl groups, and optionally substituted phenyl groups, said phenyl groups being eventually substituted with one
 20 or more groups independently selected from halogen atoms and methyl groups.

 5. The method according to any one of Claims 1 to 4, wherein the incubation step is implemented in a nitrogen medium.

 6. The method according to any one of Claims 1 to 5, wherein the microalgae is selected from microalgae of the diatom phylum, the Chromalveolata phylum, and the
 25 Archaeplastidae phylum.

 7. The method according to Claim 6, wherein the microalgae is selected from the diatom micro-algae species *Phaeodactylum tricornutum* and *Thalassiosira pseudonana*, the Chromalveolata micro-algae species *Nannochloropsis*, and the Archaeplastidae micro-algae species *Chlamydomonas*, *Ostreococcus*, and *Chlorella*.

30 8. The method according to Claim 7, wherein the microalgae is selected from the diatom micro-algae species *Nannochloropsis gaditana*, *Nannochloropsis oceanica*, and *Nannochloropsis salina*.

9. The method according to any one of Claims 1 to 8, wherein the inhibitor of sterol metabolism is selected from Ethinylestradiol, Estrone, Butenafine, Mevastatin, Simvastatin, and Terbinafine.

10. A method for producing fatty acids comprising a triggering of triacylglycerols accumulation step in microalgae as defined in any one of Claims 1 to 9, followed by an extraction step of the triacylglycerols accumulated in the microalgae to yield fatty acids in the form of triacylglycerols.

11. A method for producing biofuels comprising the following steps:

(i) a triggering of triacylglycerols accumulation step in microalgae as defined in any one of Claims 1 to 9, followed by

(ii) an extraction step of the triacylglycerols accumulated in microalgae during step (i), and

(iii) a trans-esterification step of the triacylglycerols recovered during step (ii) to obtain biofuels.

12. A method for producing pharmaceutical or cosmetic compositions comprising the following steps:

(i') a triggering of triacylglycerols accumulation step in microalgae as defined in any one of Claims 1 to 9, followed by

(ii') an extraction step of the triacylglycerols accumulated in microalgae during step (i'), and

(iii') a step of adding at least one pharmaceutically or cosmetically acceptable excipient to the triacylglycerols recovered during step (ii') to obtain pharmaceutical or cosmetic compositions.

13. A method for producing food supplements comprising the following steps:

(i'') a triggering of triacylglycerols accumulation step in microalgae as defined in any one of Claims 1 to 9, followed by

(ii'') an extraction step of the triacylglycerols accumulated in microalgae during step (i''), and

(iii'') a step of adding at least one food additive to the triacylglycerols recovered during step (ii'') to obtain food supplements.

14. Use of an inhibitor of sterol metabolism chosen from the compounds of formula (I), (II) and (III), as defined in any one of claims 1 to 4, to accumulate triglycerides in microalgae.

15. The use according to Claim 14, wherein the inhibitor of sterol metabolism is chosen from Ethinylestradiol, Estrone, Butenafine, Mevastatin, Simvastatin, Terbinafine, or combination thereof.

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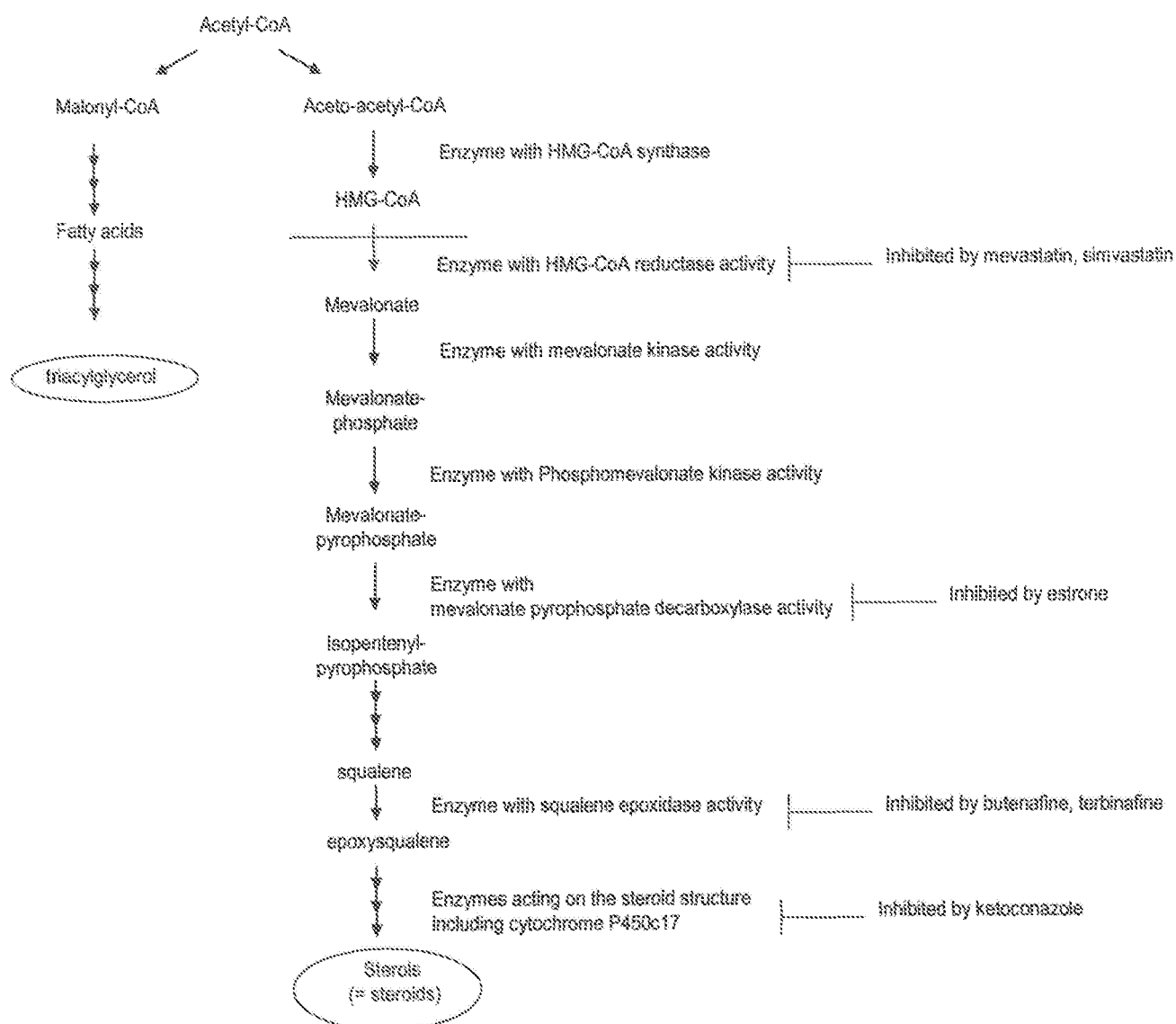


FIGURE 1

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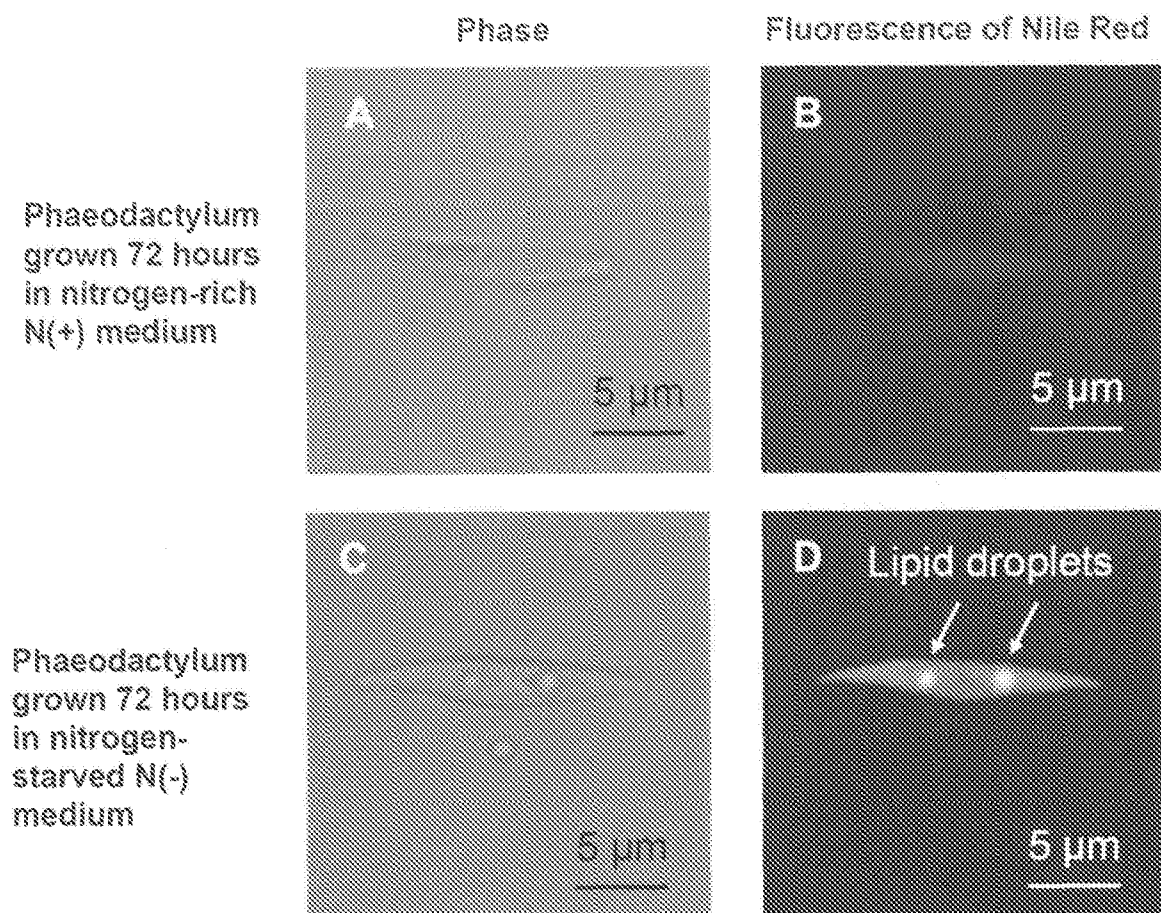


FIGURE 2

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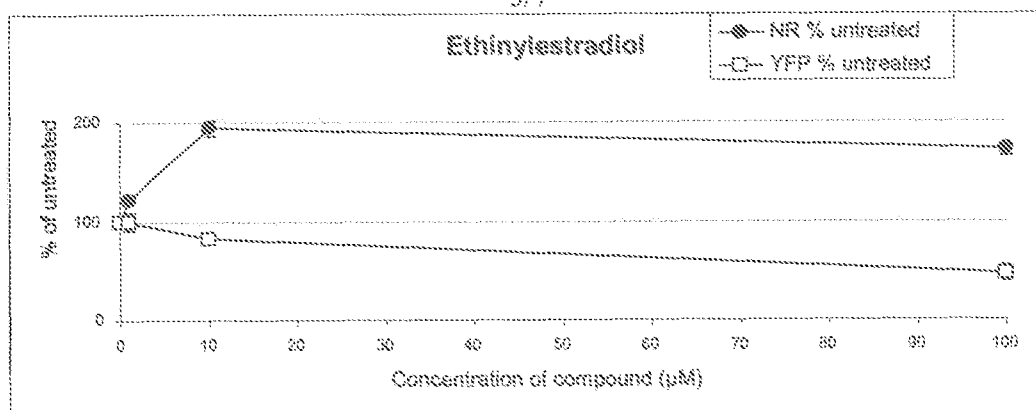


Figure 3a

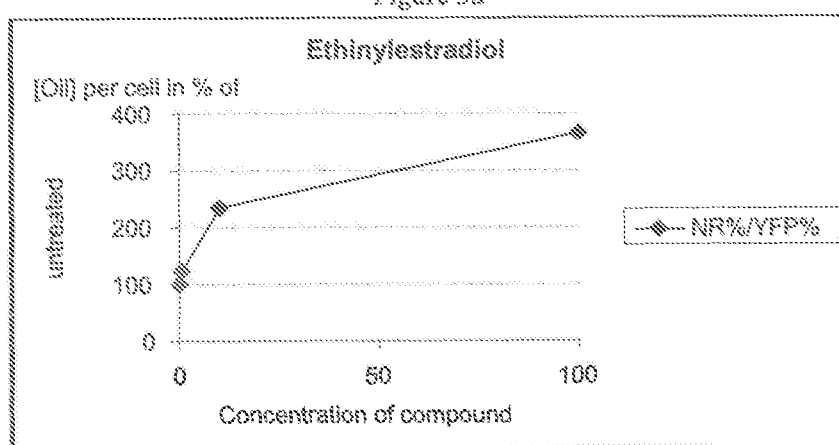


Figure 3b

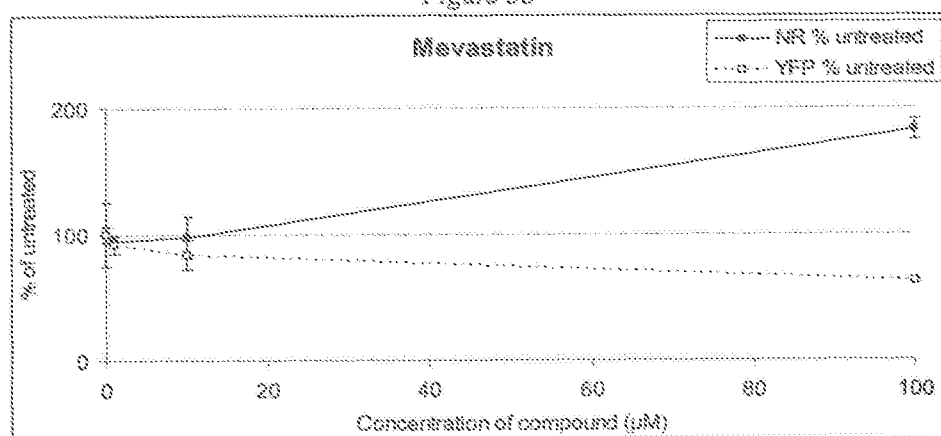


Figure 3c

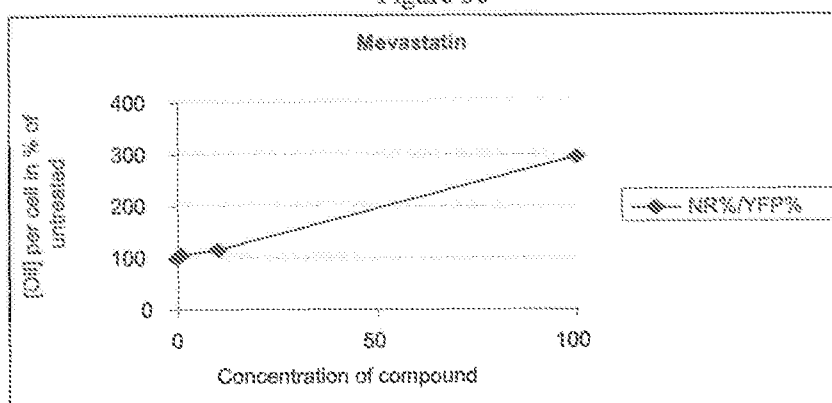


Figure 3d

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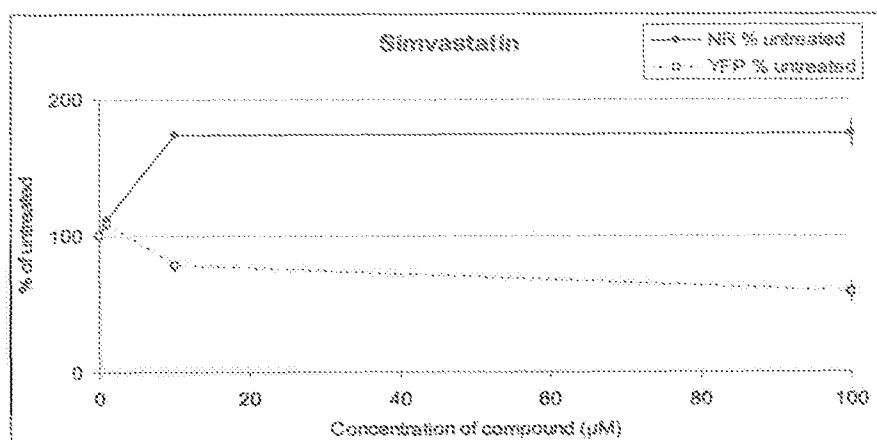


Figure 3e

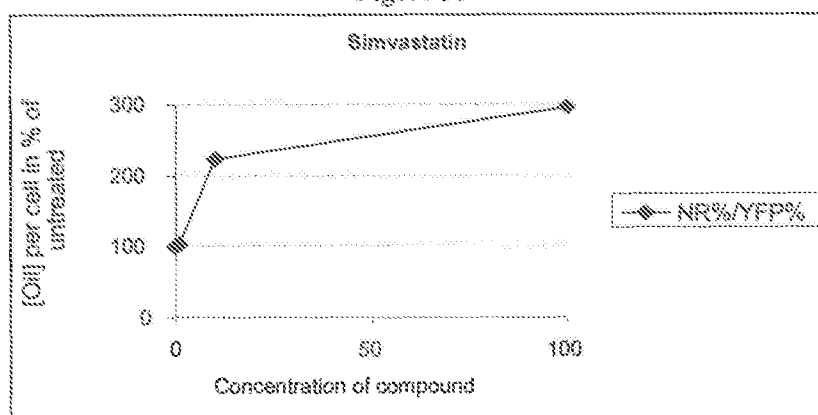


Figure 3f

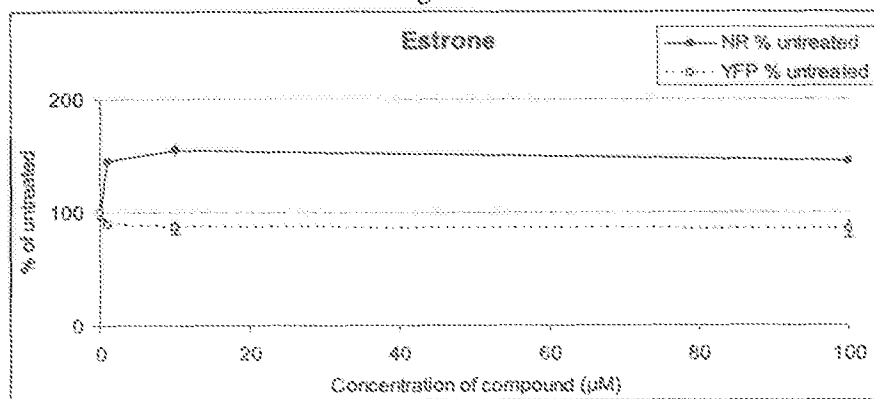


Figure 3g

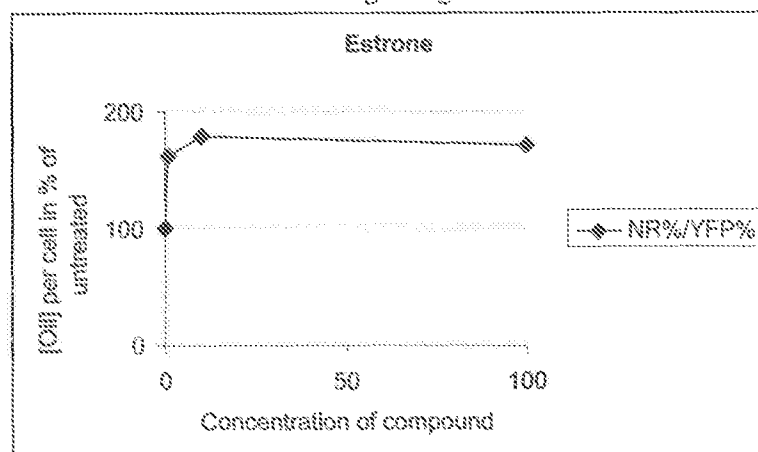


Figure 3h

FIGURE 3

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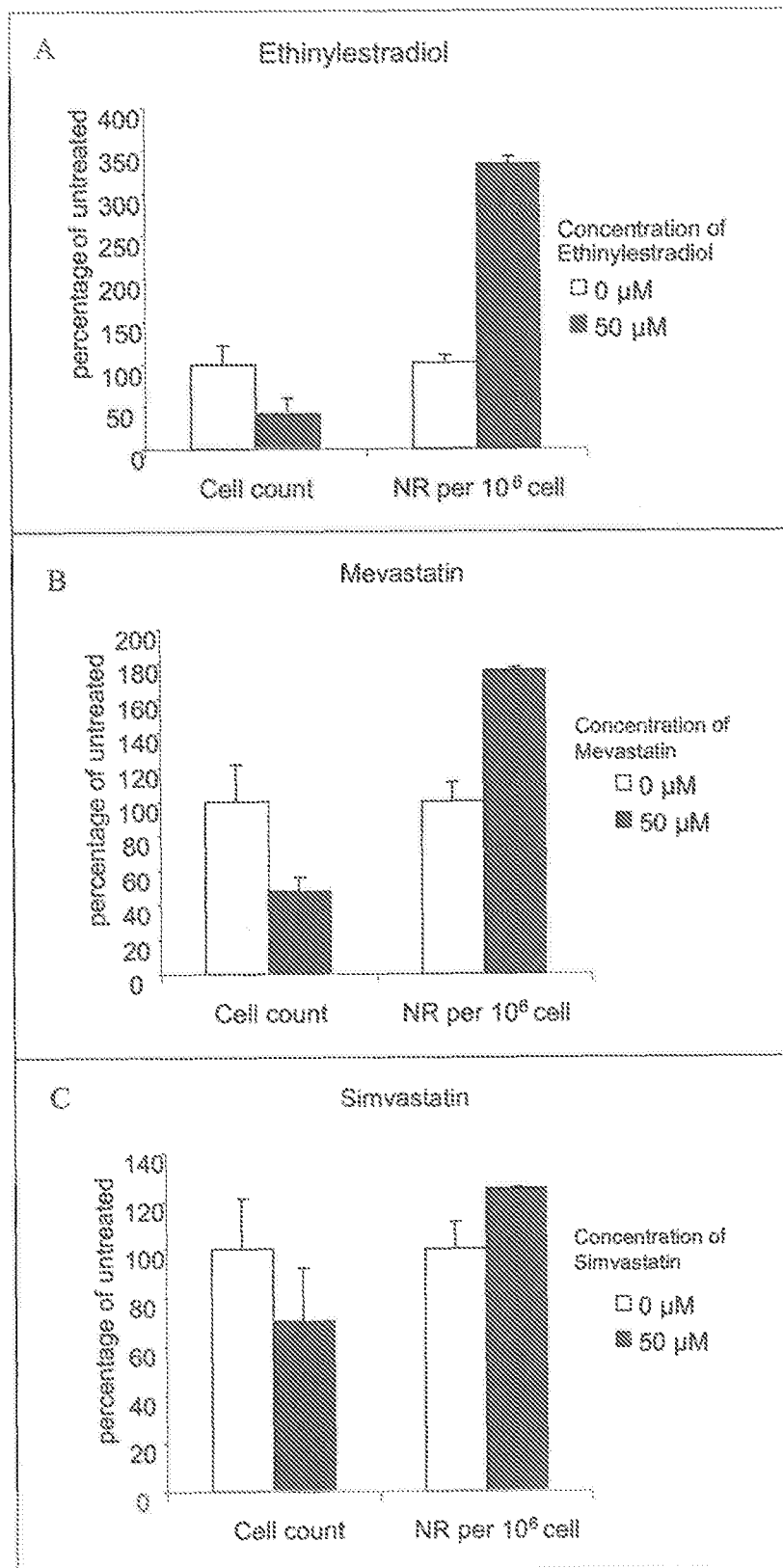


FIGURE 4

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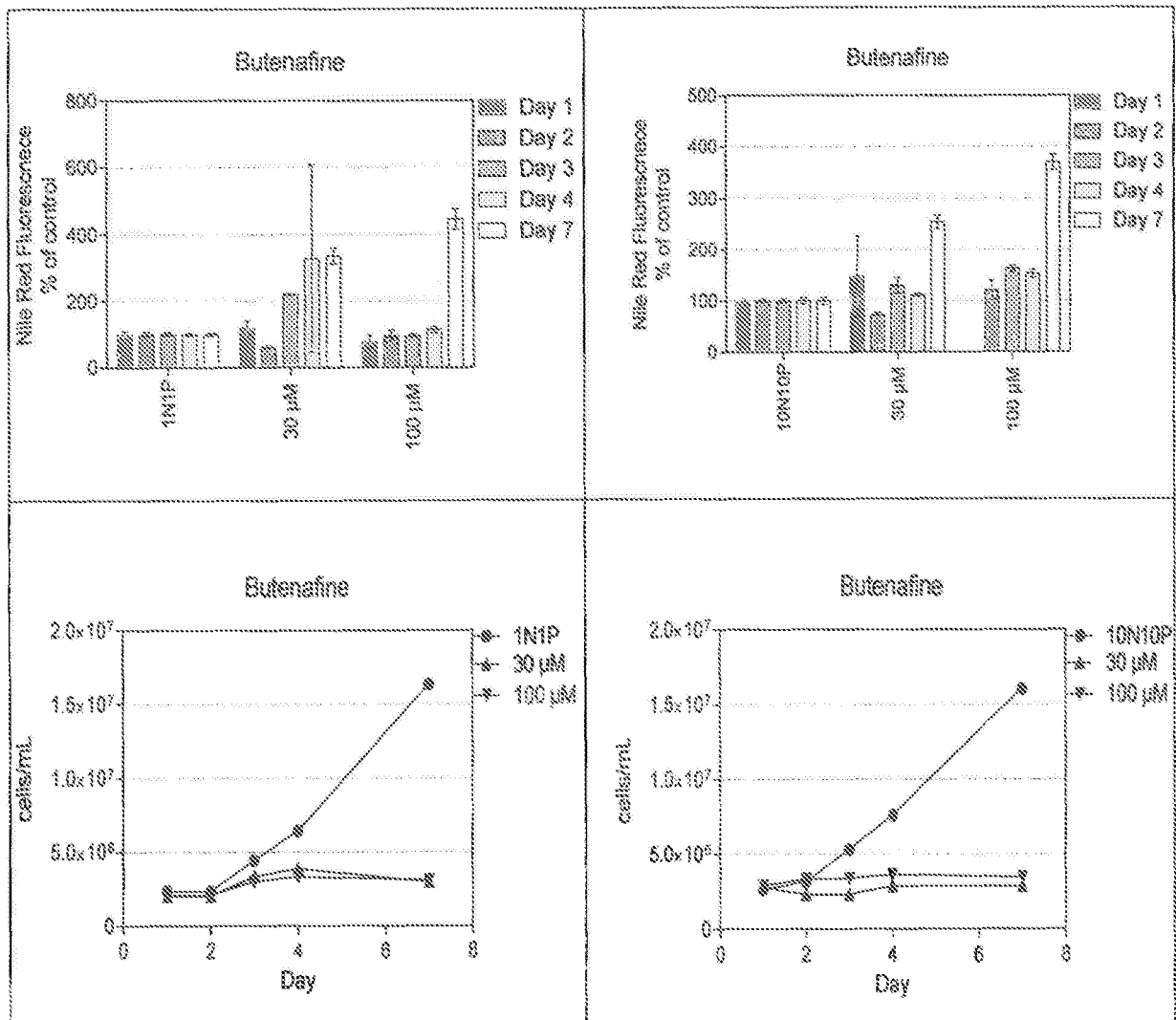


FIGURE 5

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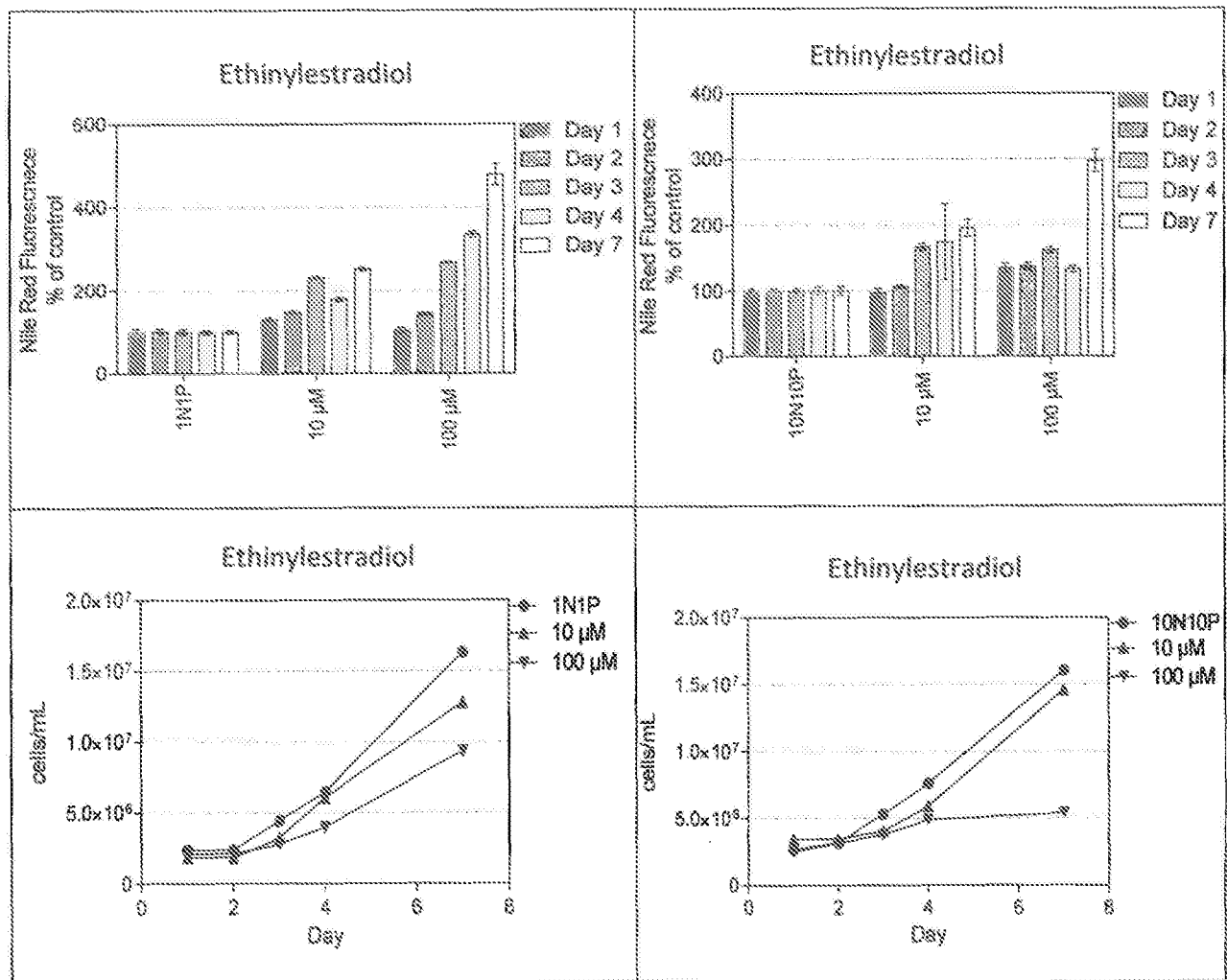


FIGURE 6