



(43) International Publication Date
22 May 2014 (22.05.2014)

(10) International Publication Number
WO 2014/077960 A1

(51) International Patent Classification:

C07H 15/02 (2006.01) *C08B 37/00* (2006.01)
C07F 9/94 (2006.01) *B01J 23/00* (2006.01)
C07H 13/06 (2006.01)

(21) International Application Number:

PCT/US2013/062575

(22) International Filing Date:

30 September 2013 (30.09.2013)

(25) Filing Language:

English

(26) Publication Language:

English

(30) Priority Data:

61/796,653 16 November 2012 (16.11.2012) US

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(81) Designated States (*unless otherwise indicated, for every
kind of national protection available*): AE, AG, AL, AM,
AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY,
BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM,
DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT,
HN, HR, HU, ID, IL, IN, IS, JP, KE, KG, KN, KP, KR,
KZ, LA, LC, LK, LR, LS, LT, LU, LY, MA, MD, ME,
MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ,
OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA,
SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM,
TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM,
ZW.

(84) Designated States (*unless otherwise indicated, for every
kind of regional protection available*): ARIPO (BW, GH,
GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, SZ, TZ,
UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ,
TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK,
EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV,
MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM,
TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW,
KM, ML, MR, NE, SN, TD, TG).

Published:

— with international search report (Art. 21(3))

(54) Title: SYNTHESIS OF CARBOHYDRATE-BASED SURFACTANTS

(57) Abstract: The present invention provides carbohydrate-based surfactants and methods for producing the same. Methods for producing carbohydrate -based surfactants include using a glycosylation promoter to link a carbohydrate or its derivative to a hydrophobic compound.



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SYNTHESIS OF CARBOHYDRATE-BASED SURFACTANTS

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the priority benefit of U.S. Provisional Application No. 61/796,653, filed November 16, 2012, which is incorporated herein by reference in its entirety.

STATEMENT REGARDING FEDERALLY FUNDED RESEARCH

[0002] This invention was made with government support under Grant Nos. CHE0714245 and CHE0133237 awarded by the National Science Foundation, Grant No. P42 ES004940 awarded by the National Institutes of Health, and Grant No. DE-FG03-93ER61526 awarded by the Department of Energy. The government has certain rights in the invention.

FIELD OF THE INVENTION

[0003] The present invention relates to novel surfactants and methods for producing the same. In particular, surfactants of the invention comprise a carbohydrate-based hydrophilic group and a lipid or a hydrocarbon hydrophobic group. Methods for producing carbohydrate-based surfactants include using a glycosylation promoter to link a carbohydrate compound or its derivative to a hydrophobic compound.

BACKGROUND OF THE INVENTION

[0004] Today's market for amphiphilic molecules, including surfactants, emulsifiers, wetting control agents, drug and gene delivery agents, microencapsulents, nanoparticle growth agents, cleaning products, and food and cosmetic additives, is mostly comprised of synthetic surfactants prepared from petroleum-based starting materials. Not only have many synthetic amphiphiles shown acute toxicities in water supplies and soil after being deposited, but they also are dependent on nonrenewable and increasingly costly petroleum. The solution to this ongoing problem is the synthesis (biological and/or chemical) of naturally-occurring (e.g. biosurfactants) or new, biodegradable amphiphilic glycolipids. Although many amphiphilic glycolipids are used in industry, they are difficult to produce on a large scale and purity is often low. A low-cost synthesis of glycolipid amphiphiles is a requirement in a market that includes many oils and synthetic amphiphiles that can be produced at pennies per pound.

[0005] As one example of biosurfactants, rhamnolipids consist of one or more rhamnose (i.e., 6-deoxy- α -L-mannose) moieties and an ester-linked di-lipid tail. They have been found in the Gram-negative bacteria such as *Acinetobacter calcoaceticus*, *Enterobacter asburiae*, *Enterobacter hormaechei*, *Pantoea stewartii*, and *Pseudomonas aeruginosa*. Biosynthetic production of rhamnolipids via the mutant strain of bacteria, *P. aeruginosa* ATCC 9027 (a mutant that produces specifically monorhamnolipids) produces about 40 different monorhamnolipid congeners with a variety of saturated and unsaturated lipid chain lengths (ranging from C₆ to C₁₈); the fully-saturated C₁₀,C₁₀ monorhamnolipid being the most dominant (~80% of mixture). Rhamnolipids, and many known amphiphilic glycolipids, are good foaming and wetting agents and are able to increase aqueous solubility of hydrophobic compounds, making them excellent solubilizing and emulsifying agents for diverse applications. In food, rhamnolipids are used as emulsifiers (e.g., partial broken fat tissue) and for influencing the rheological properties of flour. In agriculture, they are used for dilution and dispersion of fertilizers and pesticides in order to increase product penetration into plants. In cosmetics, they are used as soaps and soap formulators. In industry, they are used for emulsion polymerization of paints and industrial coatings. In the pharmaceutical industry, they are used to influence hydrophobicity of Gram-negative cell walls, allowing for easier attack by hydrophobic antibiotics. Furthermore, rhamnolipids have been shown to be environmentally friendly, expressing low toxicity and biodegradable characteristics, as well as showing strong evidence for bioremediation of hydrocarbons, organic pollutants (including green-house gases), and heavy-metal contamination.

[0006] Many amphiphiles are naturally-occurring materials that are biosynthesized and extracted from animals, plants and bacteria. However, these compounds are difficult to biosynthesize on a large scale, and purification can be difficult to impossible if a complex mixture of congeners is produced. Based on their putative biodegradability and low toxicity, biosurfactants and other amphiphilic glycolipids have great potential as “green” alternatives to the sometimes carcinogenic and toxic synthetic amphiphiles in the market. More specifically, large-scale production of the glycolipid class of biosurfactants is of great interest because of their excellent surfactant characteristics, their demonstrated use in bioremediation; the existence of evidence supporting their susceptibility to biodegradation, and their applications from paper, plastics, cosmetics, foods, pesticides, medicine, etc.

[0007] While there is a high demand for these carbohydrate or a derivative-based surfactants, conventional methods for producing such surfactants require utilizing bacteria or other microorganisms, which significantly increases their production and purification costs. In addition, microorganism based biosurfactant production limits the number of biosurfactants that can be produced and, therefore, surfactant's properties cannot be readily tailored. Many chemical processes for producing biosurfactants often utilize a toxic material or are low yielding, thereby rendering many such processes not commercially viable.

[0008] Therefore, there is a need for a cost-effective and environmentally friendly method for producing biosurfactants such as carbohydrate- or its derivative-based surfactants.

SUMMARY OF THE INVENTION

[0009] Syntheses of glycolipids typically involve expensive and toxic reagents, dangerous procedures, and low yielding reactions. Methods of the invention minimize or eliminate these problems and limitations. In one particular embodiment, methods of the invention include a cost-effective glycosylation reaction that utilizes a glycosylation promoter. The generality of the methods of the invention allows for synthesis of a broad array of carbohydrate-based surfactants such as glycolipids. Moreover, methods of the invention minimize the number of reaction steps, cost, and time compared to conventional glycolipid syntheses.

[0010] One particular aspect of the invention provides a method for producing a surfactant, said method comprising contacting a hydrophilic compound with a hydrophobic compound in the presence of a catalytic amount of a bismuth-based promoter under conditions sufficient to form a covalent bond between said hydrophilic compound and said hydrophobic compound to produce a surfactant, wherein said hydrophobic compound comprises a functional group selected from the group consisting of an amine group, a hydroxyl group and a thiol group. The heteroatom (e.g., O, N, or S) of the functional group of said hydrophobic compound becomes attached to the hydrophilic compound.

[0011] In one embodiment, said bismuth-based promoter comprises bismuth trifluoromethanesulfonate, bismuth halide, or a mixture thereof.

[0012] Yet in other embodiments, the amount of bismuth-based promoter is about 0.25 equivalent or less.

[0013] Still in other embodiments, the amount of bismuth-based promoter is about 0.1 equivalent or less.

[0014] In other embodiments, said hydrophilic compound is a carbohydrate or a derivative thereof. Within these embodiments, in some instances said carbohydrate comprises a hydroxy protecting group. Suitable hydroxy protecting groups for methods of the invention include, but are not limited to, are esters such as acetyl, benzoyl, trifluoroacetyl, propanoyl, formyl, etc.

[0015] Yet in other embodiments, said hydrophobic compound is a hydrocarbon compound of the formula: R^x-X , where R^x is hydrocarbon and X is $-OH$, $-NH_2$ or $-SH$. In some instances, R^x is alkyl. Still in other instances X is $-OH$ or $-SH$. Yet in other instances X is $-OH$.

[0016] In some embodiments, said hydrophobic compound comprises (e.g., R^x is) a C_6 - C_{30} alkyl chain. Typically, said hydrophobic compound comprises a C_6 - C_{18} alkyl chain.

[0017] Another aspect of the invention provides a method for producing a glycolipid, said method comprising contacting a carbohydrate with a lipid in the presence of a catalytic amount of a bismuth-based glycosylation promoter under conditions sufficient to produce a glycolipid, wherein said lipid comprises a glycosylation functional group selected from the group consisting of an amine group, a hydroxyl group and a thiol group, and wherein said lipid is glycosylated at said glycosylation functional group.

[0018] Yet other aspects of the invention provide a method for producing a carbohydrate- or its derivative-based surfactant, said method comprising contacting a carbohydrate or its derivative with a hydrophobic compound in the presence of a catalytic amount of a glycosylation promoter under conditions sufficient to form a covalent bond between said carbohydrate or its derivative and said hydrophobic compound to produce a carbohydrate- or its derivative based surfactant, wherein said hydrophobic compound comprises a functional group selected from the group consisting of an amine group, a hydroxyl group and a thiol group, and wherein the

functional group of said hydrophobic compound covalently links said hydrophobic compound to said carbohydrate or its derivative.

[0019] In some embodiments, said glycosylation promoter comprises a bismuth (III) compound, a scandium (III) compound, a boron compound, an indium (III) compound or a mixture thereof. Yet in other embodiments, said glycosylation promoter comprises a bismuth (III) compound. Within these embodiments, in some instances said bismuth (III) compound comprises bismuth trifluoromethanesulfonate, bismuth halide, or a mixture thereof.

[0020] Yet in other embodiments, the amount of glycosylation promoter used in the reaction is about 0.25 equivalent or less. It should be appreciated that the term “equivalent” is relative to the amount of either the hydrophilic or the hydrophobic compound used in the reaction, whichever is less.

[0021] Still in some embodiments, said hydrophobic compound is a hydrocarbon compound of the formula: R^x-X , where R^x and X are those defined herein.

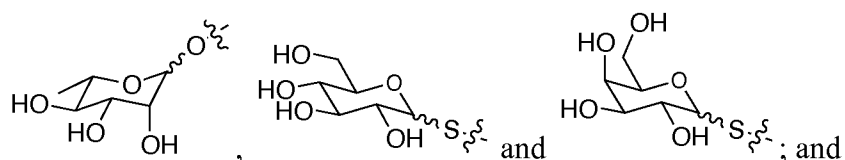
[0022] In other embodiments, said hydrophobic compound comprises a C_6 - C_{30} alkyl chain. Within these embodiments, in some instances said hydrophobic compound comprises a C_6 - C_{18} alkyl chain.

[0023] Still other aspects of the invention provides a carbohydrate- or its derivative-based surfactant of the formula:

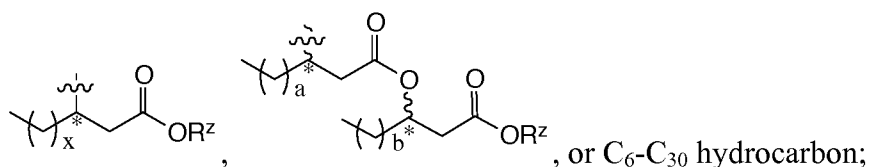
A-B

wherein

A is selected from the group consisting of:



B is selected from the group consisting of:



and wherein

R^Z is hydrogen, alkyl, benzyl, or other carboxylic acid protecting group;

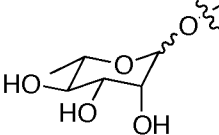
x is an integer from 6 to 14;

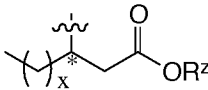
a is an integer from 2 to 18;

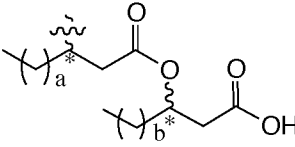
b is an integer from 2 to 18; and

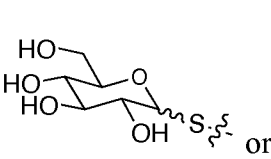
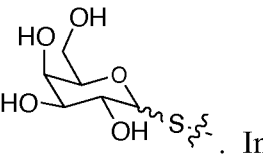
* is a chiral center.

[0024] In some embodiments, C_6 - C_{30} hydrocarbon is C_6 - C_{30} alkyl.

[0025] In one particular embodiment, A is . In some instances within

this embodiment, B is , wherein R^Z , x and * are those defined herein. In some

cases, x is 6, 10, 12 or 14. Still in other instances, B is , wherein a, b and * are those defined herein. In some cases, a is 2, 6, 10, 12 or 14. In other cases, b is 2, 4, 6, 8, 10, 12 or 14. Yet in other instances, B is C_9 or C_{10} alkyl. In some cases, B is a straight chain C_9 or C_{10} alkyl. Typically, 1- or 2- position of C_9 or C_{10} alkyl is linked to A.

[0026] Still in another embodiment, A is  or . In some instances, B is C_6 - C_{30} alkyl. In one particular case, B is dodecyl.

DETAILED DESCRIPTION OF THE INVENTION

Definitions

[0027] When referring to a nonpolar or hydrophobic alkyl group, the term “alkyl” refers to a monovalent saturated linear monovalent hydrocarbon moiety or a saturated branched monovalent hydrocarbon moiety of six to thirty, typically six to twenty two, often six to twenty and more often six to eighteen carbon atoms. Exemplary nonpolar alkyl groups include, but are not limited to, hexyl, decyl, dodecyl, tetradecyl, hexadecyl, octadecyl, and the like.

[0028] A nonpolar or hydrophobic “alkenyl” group refers to a linear monovalent hydrocarbon moiety or a branched monovalent hydrocarbon moiety having at least one carbon-carbon double bond in which the total carbon atoms is six to thirty, typically six to twenty two, often six to twenty and more often six to eighteen. Exemplary nonpolar alkenyl groups include, but are not limited to, hexyl, decyl, dodecyl, hexadeca-1,3-dienyl, docosaheptaenyl, dodeca-2,4-dienyl, and the like.

[0029] A nonpolar or hydrophobic “alkynyl” group refers to a linear monovalent hydrocarbon moiety or a branched monovalent hydrocarbon moiety having at least one carbon-carbon triple bond in which the total carbon atoms is six to thirty, typically six to twenty two, often six to twenty and more often six to eighteen. Alkynyl group can optionally have one or more alkenyl moiety (i.e., carbon-carbon double bond). Exemplary nonpolar alkynyl groups include, but are not limited to, hexynyl, decynyl, dodecynyl, hexadeca-1,3-diynyl, dodecynyl, dec-1-en-3-ynyl and the like.

[0030] The terms “halo,” “halogen” and “halide” are used interchangeably herein and refer to fluoro, chloro, bromo, or iodo.

[0031] The term “hydrocarbon” includes alkyl, alkenyl, or alkynyl as defined herein. It should be appreciated that one or more of the hydrogen in alkyl, alkenyl, or alkynyl may be substituted with halide. Unless stated otherwise, hydrocarbon can also include a cyclic (alkyl, alkenyl or alkynyl) group or an aryl group, provided that the overall polarity of the hydrocarbon remains relatively nonpolar.

[0032] The term “hydrophobic” group refers to any moiety having at least six carbon atoms in which in the absence of the hydrophilic portion of the surfactant is substantially immiscible or insoluble in aqueous solution. Typically, solubility of the parent hydrophobic group (i.e., where the hydrophilic portion of the surfactant is replaced with hydrogen or the corresponding functional group) in water is about 10 g/L or less, often 1 g/L or less, more often 0.5 g/L or less, and most often 0.1 g/L or less. The hydrophobic group can have other functional groups (e.g., ether, ester, halide, etc.) as long as the solubility of the parent compound satisfies the conditions set forth herein. Thus, the term hydrophobic group includes hydrocarbons defined herein as well as lipids, and other groups in which the parent compound meets the conditions set forth herein.

[0033] “Aryl” refers to a monovalent mono-, bi- or tricyclic aromatic hydrocarbon moiety of 6 to 15 ring carbon atoms which is optionally substituted with one or more, typically one, two, or three substituents within the ring structure. When two or more substituents are present in an aryl group, each substituent is independently selected. Typical substituents for an aryl group include, but are not limited to, alkyl, alkenyl, alkynyl, and halide.

[0034] The term “derivative” refers to any chemical modification of the parent compound or a compound derived from the parent compound. For example, a derivative of a carbohydrate includes alkylated carbohydrate, replacement of one or more hydroxyl groups with hydrogen, halide, amine, or a thiol; modification of a hydroxyl group (e.g., by esterification, etherification, protection, etc.); as well as other derivatives known to one skilled in the art. The term carbohydrate includes pyranose and furanose carbohydrates. Exemplary derivatives of carbohydrates include, but are not limited to, alkylated carbohydrate (e.g., one or more hydroxyl groups that are methylated, ethylated, acetylated, or benzoylated), thiol carbohydrate (where one or more hydroxyl groups are replaced with –SH moiety), deoxy carbohydrates (where one or more –OH groups of the carbohydrate is replaced with –H), etc.

[0035] Unless the context requires otherwise, the term “promoter” refers to a compound that facilitates or aids in linking a hydrophilic compound with a hydrophobic compound to produce a surfactant. The promoter itself does not become part of the final product (i.e., surfactant) but merely facilitates formation of a bond between the hydrophilic group and the hydrophobic group. A promoter can be a catalyst, in which case less than 1 equivalent can be used, or it can be stoichiometric, requiring at least 1 equivalent.

[0036] “Protecting group” refers to a moiety, except alkyl groups, that when attached to a reactive group in a molecule masks, reduces or prevents that reactivity. Examples of protecting groups can be found in T.W. Greene and P.G.M. Wuts, *Protective Groups in Organic Synthesis*, 3rd edition, John Wiley & Sons, New York, 1999, and Harrison and Harrison et al., *Compendium of Synthetic Organic Methods*, Vols. 1-8 (John Wiley and Sons, 1971-1996), which are incorporated herein by reference in their entirety. Representative hydroxy protecting groups include acyl groups, benzyl and trityl ethers, tetrahydropyranyl ethers, trialkylsilyl ethers and allyl ethers. Representative amino protecting groups include, formyl, acetyl, trifluoroacetyl, benzyl, benzyloxycarbonyl (CBZ), *tert*-butoxycarbonyl (Boc), trimethyl silyl (TMS), 2-

trimethylsilyl-ethanesulfonyl (SES), trityl and substituted trityl groups, allyloxycarbonyl, 9-fluorenylmethyloxycarbonyl (FMOC), nitro-veratryloxycarbonyl (NVOC), and the like.

[0037] “Corresponding protecting group” means an appropriate protecting group corresponding to the heteroatom (i.e., N, O, P or S) to which it is attached.

[0038] When describing a chemical reaction, the terms “treating”, “contacting” and “reacting” are used interchangeably herein, and refer to adding or mixing two or more reagents under appropriate conditions to produce the indicated and/or the desired product. It should be appreciated that the reaction which produces the indicated and/or the desired product may not necessarily result directly from the combination of two reagents which were initially added, i.e., there may be one or more intermediates which are produced in the mixture which ultimately leads to the formation of the indicated and/or the desired product.

Surfactants

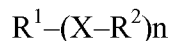
[0039] Surfactants are compounds that lower the surface tension (or interfacial tension) between two liquids or between a liquid and a solid. Typically, surfactants are amphiphilic organic compounds that can form aggregates in solution and ordered assemblies at interfaces. Surfactants can act as detergents, wetting agents, emulsifiers, foaming agents, and dispersants. Surfactants typically include two different groups, a hydrophilic or polar group and a hydrophobic or a nonpolar group. Typical hydrophobic groups of a surfactant are a lipid or other nonpolar hydrocarbon group such as an alkyl, alkenyl, or alkynyl. However, it should be appreciated that suitable nonpolar groups for a surfactant are not limited to these groups and can include any nonpolar groups including cyclic hydrocarbon group, aromatic hydrocarbon group, etc.

[0040] When placed in an aqueous solution, surfactants form a micelle where the lipophilic tails of the surfactant remain on the inside of the micelle due to its hydrophobicity. The polar “heads” of the micelle, due to its hydrophilic property, form a hydrophilic outer layer that in effect protects the hydrophobic core of the micelle. It should be noted that surfactants are soluble not only in polar protic solvents such as water but also in polar aprotic and non-polar solvents as a reverse micelle.

[0041] Thus surfactants are useful in a wide variety of applications including, but not limited to, household detergents, industrial and institutional cleaning, personal care products, crop protection, agricultural dispersants, oil drilling and extraction, paints and coatings, textile spin finishes, textile auxiliaries, construction, emulsion polymerization, food additives, leather production, mining, plastics additives, pulp and paper, explosives, remediation, wetting control agents, pharmaceuticals, drug delivery agents, etc.

[0042] Unfortunately, conventional surfactant syntheses are typically toxic or have a high environmental impact in that toxic chemicals do not degrade readily and can last for years. Current “green” alternatives for surfactants include biosurfactants and other naturally-occurring and/or bio-inspired surfactants. However, these green surfactants are typically limited to known biosurfactants and, therefore, surfactant’s properties cannot be readily tailored.

[0043] Some aspects of the invention are directed to surfactants that are biodegradable and have generally low toxicity. Other aspects of the invention provide methods for producing the same. In particular, surfactants of the invention are of the formula:

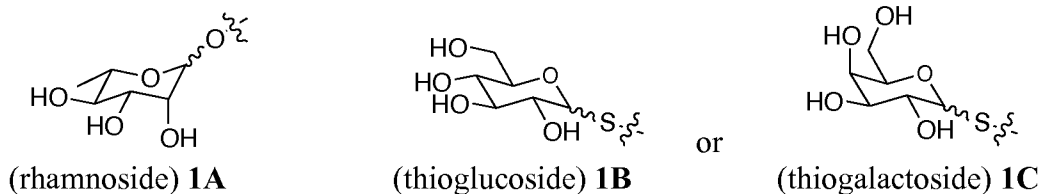


where R^1 is a hydrophilic group, R^2 is a hydrophobic group, each X is independently a functional group that links the hydrophilic group with the hydrophobic group; and n is an integer of at least 1 and up to the number of functional groups present in R^1 . Typically n is 1 to 3, often 1 to 2, and more often 1.

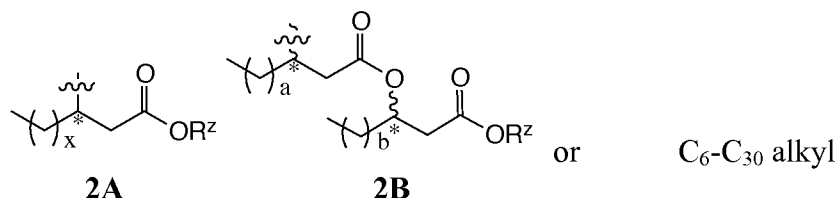
[0044] In one particular embodiment, the hydrophilic group is a carbohydrate or a derivative thereof. Exemplary hydrophilic groups of the invention include galactose, glucose, lactose, maltose, mannose, rhamnose, sophorose, arabinose, and 2-, 3-, and/or 5-deoxy derivatives thereof. The carbohydrate moiety can be a pyranose (or pyranoside, i.e., 6-membered ring) or a furanose (or furanoside, i.e., 5-membered ring) form. In addition, the carbohydrate can be mono-, di- or polysaccharides.

[0045] Surfactants of the invention also include a hydrophobic group such as a lipid or a hydrocarbon moiety. Typically surfactants of the invention include a single or multiple hydrocarbon chains of varying lengths with different pendant functional groups. In particular, the hydrophobic moiety is often used to tune surfactant or emulsifying behavior of surfactants.

[0046] Some of the particular surfactants of the invention include a hydrophilic moiety of the formula:



with the following hydrophobic groups:



where R^z is hydrogen, alkyl, benzyl, or other carboxylic acid protecting group; x is an integer from 6 to 14, in particular 6 or 10; a is an integer from 2 to 18, typically 2 to 16, in particular 2, 6, 10, 12 or 14; b is an integer from 2 to 18, typically 2 to 16, in particular 2, 4, 6, 8, 10, 12 or 14. Typically, alkyl group is C₆-C₂₂ alkyl, in particular alkyl group is C₈, C₉ or C₁₂ alkyl. The hydrophilic group is typically attached to the 1-, 2-, or the 3-position of the hydrophobic group; however, it should be appreciated that the scope of the invention is not limited to these positions of substitution. In one particular embodiment, the alkyl hydrophobic group is a linear chain alkyl group. It should also be appreciated that each chiral center of the hydrophobic group (e.g., each chiral carbon atom indicated by *) can be independently enantiomerically enriched (R)- or (S)-stereoisomer, or a racemic mixture.

[0047] Still further, combinations of the various hydrophilic groups and hydrophobic groups described herein form other specific embodiments of the invention. For example, in one particular embodiment the hydrophilic group is rhamnose and the hydrophobic group is **2A** where x is 6, 10, 12 or 14; in another embodiment, the hydrophilic group is rhamnoside and the hydrophobic group is **2B** where a is 2, 6, 10, 12 or 14 and b is 2, 4, 6, 8, 10, 12 or 14. Still in another embodiment, the hydrophilic group is rhamnose and the hydrophobic group is C₉ or C₁₀ alkyl. Within this embodiment, in some instances C₉ or C₁₀ alkyl is a straight chain alkyl in which the 2-position is attached to rhamnose. In still another example, the hydrophilic group is glucose, galactose or dodecyl. It should be appreciated that the functional group that links the

hydrophilic group to the hydrophobic group is derived from the functional group that is present in the hydrophobic compound, e.g., the thiol group in moieties **2A** and **2B** are derived from the functional group of hydrophobic compound. Within this embodiment, in some instances the 1-position of dodecyl is attached to the hydrophilic group. In this manner, a variety of surfactants are embodied within the invention.

Synthesis

[0048] There are a variety of publications and patents providing many different chemical syntheses for glycolipids; however, many of these methods are specific to a single carbohydrate and single lipid; these procedures range from solid-phase to solution-phase techniques at low or high temperatures, the latter reactions being achieved by microwave or conventional heating. However, microwave-assisted reactions can be limited in scalability. Additionally, many chemical methodologies for glycolipids require multiple reaction steps in order to prepare glycosyl compounds for glycosylation with lipids. Furthermore, conventional glycosylation procedures can be expensive, dangerous, and some even require non-catalytic amount of a relatively expensive and/or toxic glycosylation promoters.

[0049] In contrast, methods of the invention can be used to produce a vast number of surfactants with a variety of carbohydrates as a hydrophilic group and a variety of hydrophobic groups including, but not limited to, lipids and hydrocarbons in a cost-effective and time-efficient manner. Because of the generality of this methodology, the synthesis and development of new species of surfactants, in particular glycolipid biosurfactants, can be achieved in order to not only compete in the markets for amphiphilic molecules, but improve these markets through the vast applicability of these glycolipids for multiple purposes. For instance, there are a variety of O- and S-linked glycolipids used in personal care products and cosmetics, and N-linked glycolipids have been shown to be excellent drug-delivery systems, such as the case with many glycopeptides.

[0050] One of the major advantages of methods of the invention is that surfactants are produced using a chemical procedure. Thus, unlike biological procedures for producing glycolipids, methods of the invention do not require extraction and purification from the bacteria. Moreover, unlike biological process-based glycolipid production, methods of the invention allow for production of single congeners that may be present in only small amounts in the congener

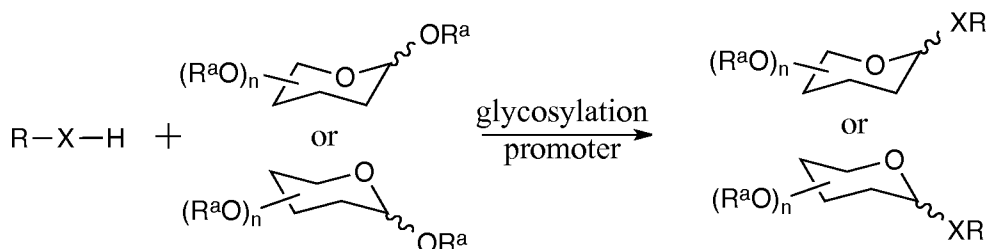
mixture produced by bacteria. Therefore, the chemical synthesis is cost-effective, high yielding, scalable and requires less time to produce a variety of glycolipids compared to biological means. Additionally, a general synthetic method allows for the simple tailoring and production of novel glycolipids. These novel glycolipids can have different physical properties and amphiphilic characteristics depending on the hydrophilic moiety and/or the hydrophobic moiety used.

[0051] In some embodiments, methods of the invention include contacting a hydrophilic compound and a hydrophobic compound in the presence of a glycosylation promoter catalyst under conditions sufficient to produce the desired surfactant. In one particular embodiment, the hydrophilic compound is a carbohydrate moiety. Within this embodiment, in some instances the hydrophilic compound is a protected carbohydrate. Typically, the protecting group of the hydroxyl group of the carbohydrate is such that it can be displaced in the reaction to produce a relatively stable anion. For example, the pKa of the counter acid of the displaced protecting group in the glycosylation reaction is about 12 or less, typically 10 or less, often 8 or less, more often 7 or less and most often 6 or less. Exemplary counter acids of the displaced protecting group include, but are not limited to, organic acids (such as acetic acid, benzoic acid, trifluoroacetic acid, butyric acid, propionic acid, etc.), as well as other compounds whose counter acids are relatively strong. In one particular instance, one or more of the hydroxyl group of the carbohydrate is protected as acetic ester or benzoic ester. While one or more of the hydroxyl groups of the carbohydrate can have different protecting group(s), for simplicity and cost-effectiveness, typically all of the hydroxyl groups of the carbohydrate is protected with the same protecting group. Thus, in some instances, the carbohydrate is a peracetate or perbenzoate carbohydrate. It should be appreciated, however, the scope of the invention is not limited to hydroxyl groups of the carbohydrate having the same protecting group.

[0052] In general, the most challenging synthetic step of conventional glycolipid synthesis is the glycosylation step. This is due to the highly reactive characteristics of common carbohydrate donors and the typical use of moisture-sensitive promoters, which can cause low-yielding reactions, side-product formation and carbohydrate degradation.

[0053] Scheme 1 illustrates one particular reaction scheme of methods of the invention. As shown in Scheme 1, typical reaction condition includes a hydrophilic compound, a hydrophobic compound, and a glycosylation promoter. The glycosylation promoters of the

invention are relatively weak Lewis acids and are used in a catalytic amount rather than in stoichiometric amount. Typically, the amount of glycosylation promoter used in methods of the invention is about 0.5 equivalent or less, typically 0.3 equiv. or less, often 0.25 equiv. or less, more often 0.2 equiv. or less, and most often 0.1 equiv. or less.



X is $-O-$, $-NH-$ or $-S-$; n is an integer from 1 to 4; R^a is typically Ac (acetyl) or Bz (benzoyl); and R is primary (i.e., 1°) or secondary (i.e., 2°) hydrophobic group

Scheme 1

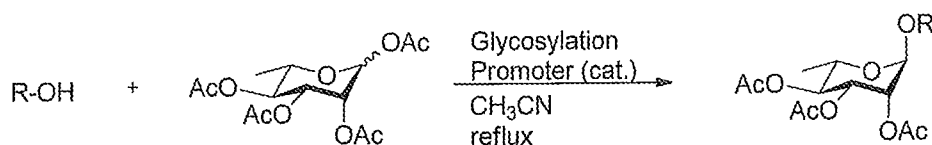
As can be seen in Scheme 1, the anomeric acetate or benzoyle is displaced in the reaction and is substituted with the hydrophobic moiety to produce the surfactant. Exemplary glycosylation promoters for this purpose include, but are not limited to, bismuth (III) compounds (e.g., bismuth (III) trifluoromethanesulfonate, bismuth (III) bromide, bismuth (III) chloride, etc.), scandium(III) compounds (e.g., scandium (III) trifluoromethanesulfonate, etc.), boron compounds (e.g., boron trifluoride diethyl etherate), and indium (III) compounds (e.g., indium (III) bromide and indium (III) chloride). Unlike conventional glycosylation reactions, methods of the invention do not require stoichiometric or even excess amounts of often expensive, unstable and/or exotic glycosylation promoters. Moreover, the reaction times in methods of the invention are typically shorter than conventional glycosylation reactions.

[0054] Typically, the glycosylation reaction of the invention is carried out in a solvent. Suitable solvents include, but are not limited to, acetonitrile, benzene, dichloromethane, chloroform, carbon tetrachloride, dibromomethane, 1,2-dichloroethane, toluene, nitrobenzene, benzonitrile, tetrahydrofuran, diethyl ether, dibutylether, diisopropylether, dimethylformamide, and a combination of two or more thereof.

[0055] Hydrophobic compounds can include primary and secondary alcohols, amines, or thiols having at least six carbon chain length. Exemplary hydrophilic compounds include carbohydrates such as rhamnose, glucose, lactose, galactose, and mannose. Typically the carbohydrate used is protected as peracetates or perbenzoyleates. However, it should be

appreciated that, as discussed above, the scope of the invention is not limited to these particular protecting groups.

[0056] The Table below shows the yield of the glycosylation between rhamnose peracetate and various alkyl alcohols (1-decanol, 2-decanol and benzyl 3-hydroxydecanoate) in the presence of glycosylation promoter $\text{Bi}(\text{OTf})_3$ or InBr_3 . All reactions were conducted at the same temperature, concentration, and reagent equivalencies for comparison of the glycosylation promoter efficiencies.



R-OH	Glycosylation Promoter	Yield (%)
1-decanol	$\text{Bi}(\text{OTf})_3$	91
	InBr_3	89
2-decanol	$\text{Bi}(\text{OTf})_3$	89
	InBr_3	83
Benzyl 3-hydroxydecanoate	$\text{Bi}(\text{OTf})_3$	60
	InBr_3	38

[0057] The result of glycosylation reactions using perbenzoylate rhamnose as the hydrophilic moiety is shown below. As can be seen, in general, the yield of the glycosylated products using a bismuth (III) compound as a glycosylation promoter is higher compared to reactions where an indium (III) compound is used as a glycosylation promoter. Moreover, generally bismuth (III) compounds are less hygroscopic and regarded as nontoxic compared to indium (III) compounds. Thus, in some embodiments, the glycosylation promoter is a bismuth (III) compound. Within these embodiments, in some instances the glycosylation promoter comprises bismuth trifluoromethanesulfonate, bismuth halide, or a mixture thereof.

Results of glycosylation using perbenzoylated rhamnose as the hydrophilic compound.

R-OH	Glycosylation Promoter	Yield (%)
1-decanol	$\text{Bi}(\text{OTf})_3$	77
	InBr_3	33
2-decanol	$\text{Bi}(\text{OTf})_3$	46
	InBr_3	24
Benzyl 3-hydroxydecanoate	$\text{Bi}(\text{OTf})_3$	33
	InBr_3	No Reaction

[0058] The table below shows the yield of glycosylation reactions using $\text{BF}_3 \cdot \text{Et}_2\text{O}$, $\text{Sc}(\text{OTf})_3$, and InBr_3 as the glycosylation promoter. As can be seen, the glycosylation reaction required at least a stoichiometric amount (i.e., 1 equivalent or more) of $\text{BF}_3 \cdot \text{Et}_2\text{O}$ and $\text{Sc}(\text{OTf})_3$ glycosylation promoters. In contrast, only a catalytic amount of InBr_3 glycosylation promoter is needed to provide a sufficiently high yield of the desired glycosylation product.

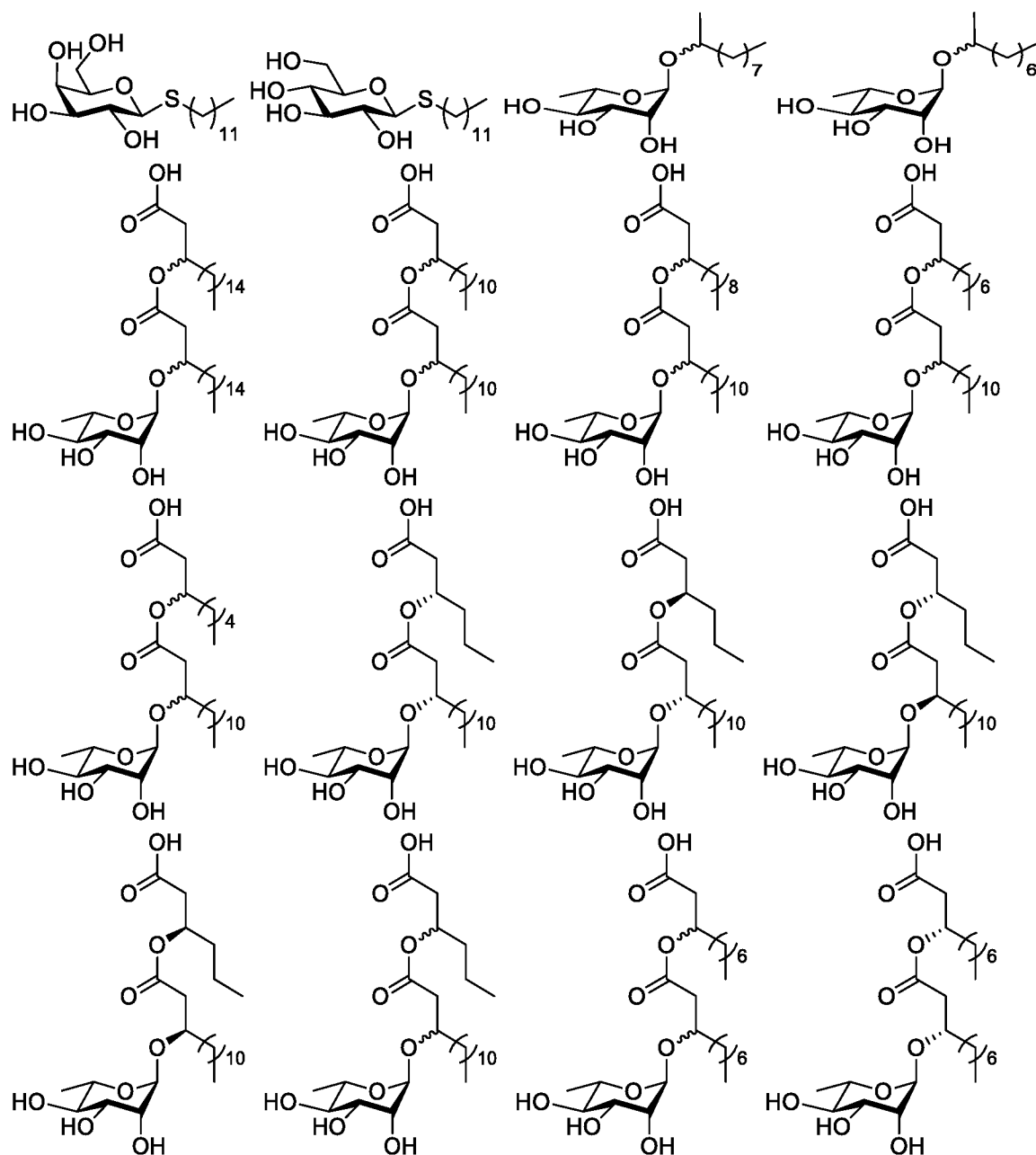
Decanol	Yield ^{b)} [%]		
	$\text{BF}_3 \cdot \text{Et}_2\text{O}$ (5.0 equiv.)	$\text{Sc}(\text{OTf})_3$ (1.0 equiv.)	InBr_3 (0.1 equiv.)
Decan-1-ol (2)	52	39	39
(±)-Decan-2-ol (3)	71	33	50
Methyl (±)-3-hydroxydecanoate (4)	43	16	34

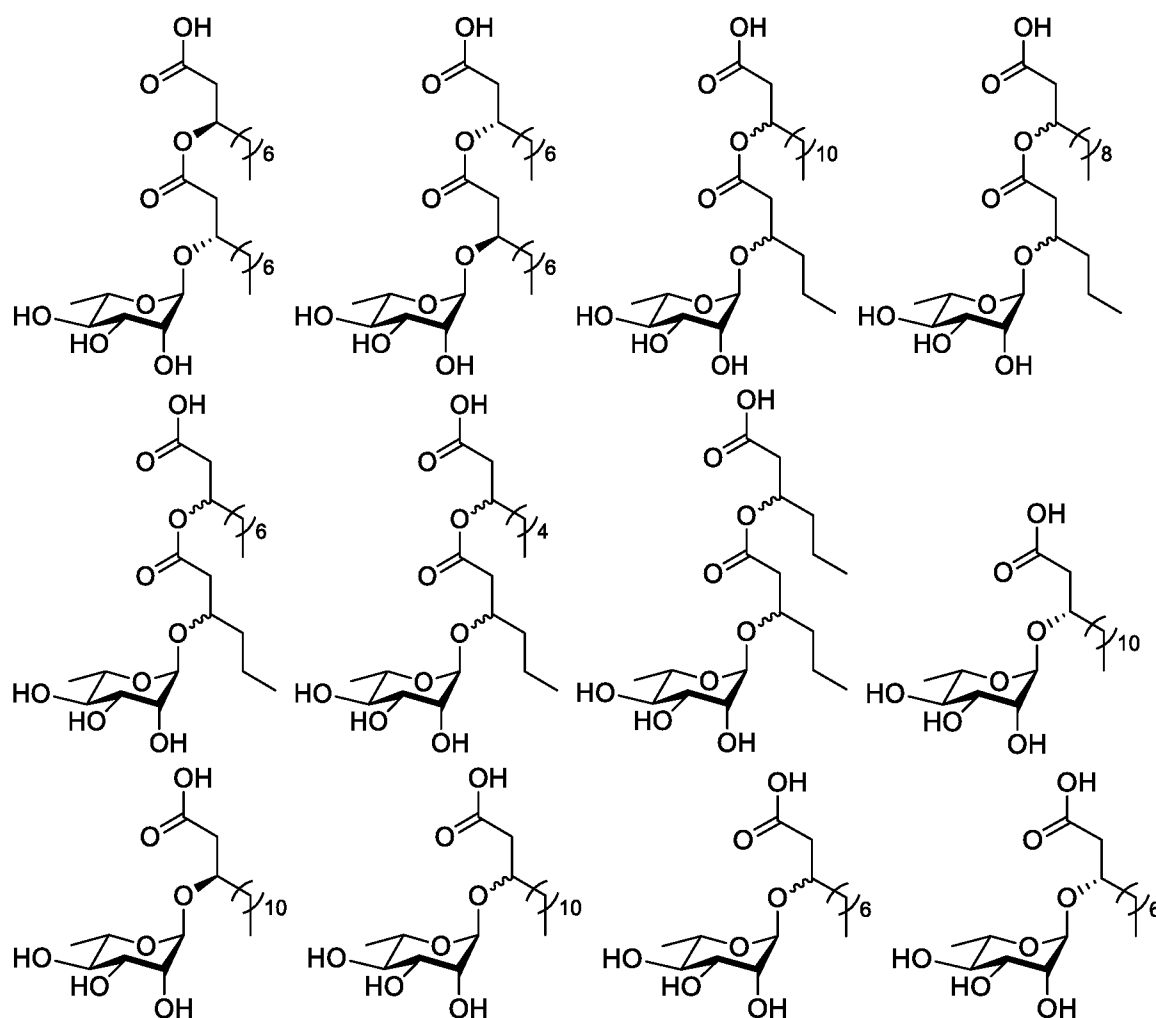
^{a)} Conditions: 2.2 equiv. of L-rhamnose peracetate **5** and 1 equiv. of decanol **2**, **3**, or **4** in CH_2Cl_2 at 60° in a sealed tube. ^{b)} Yield of **6** (from **2**), **7** (from **3**), and **8** (from **4**).

[0059] A wide range of reaction temperatures can be used in methods of the invention. Typically, the reaction temperature used for glycosylation depends on a variety of factors including the glycosylation promoter, hydrophilic compound, hydrophobic compound, solvent, as well as the concentrations of each reagent used. Typically, glycosylation is carried out at the reaction temperature of 30 °C or higher, often 40 °C or higher, more often 50 °C or higher, and most often at the boiling point of solvent.

[0060] The hydroxy protecting groups can be removed using a standard deprotection reaction known to one skilled in the art. See, for example, T.W. Greene and P.G.M. Wuts, *Protective Groups in Organic Synthesis*, 3rd edition, John Wiley & Sons, New York, 1999, and Harrison and Harrison et al., *Compendium of Synthetic Organic Methods*, Vols. 1-8 (John Wiley and Sons, 1971-1996), which are incorporated herein by reference in their entirety. In this manner, a wide variety of carbohydrate-based surfactants are produced using the methods of the

invention. Representative compounds that are produced using the methods of the invention include, but are not limited to, the following compounds:





[0061] Additional objects, advantages, and novel features of this invention will become apparent to those skilled in the art upon examination of the following examples thereof, which are not intended to be limiting. In the Examples, procedures that are constructively reduced to practice are described in the present tense, and procedures that have been carried out in the laboratory are set forth in the past tense.

EXAMPLES

[0062] All glassware was flame-dried prior to reactions, and all reactions were done under Ar. Microwave: 900W Emerson MW8992SB microwave oven, purchased from a Target department store. Flash chromatography (FC): silica gel 60 (SiO₂, 200 – 400 mesh; Geduran No. EM-11567-1); Horizon HPFC system (Biotage, Inc.). HPLC: Varian-Prostar HPLC system, with a Prostar-330 photodiode array detector and a Phenomenex-Jupiter (250 mm x 21.2 mm, 15 μm)

C₁₈ semi-prep. column. M.p.: uncorrected. ¹H and ¹³C NMR Spectra: Bruker-DRX-400 (400 MHz), -DRX-500 (500 MHz), and -DRX-600 (600 MHz) spectrometers; in CDCl₃, (D₆)DMSO, or CD₃OD; δ in ppm rel. to Me₄Si as internal standard, J in Hz; all NMR spectra were analyzed and interpreted with the MestReNova software. ESI-MS: Thermo-Finnigan LCQ Deca with pos. and neg. detection, MeOH/H₂O 1:1 solvent system; in m/z (rel. %).

[0063] Decyl β-Lactoside. A mixture of potassium acetate (i.e., AcOK) (6.56 g, 66.8 mmol) and acetic anhydride (i.e., Ac₂O) (21 ml, 220 mmol) was heated under reflux, followed by slow addition of lactose (1.01 g, 2.79 mmol) to the boiling mixture. The mixture was stirred for 5 min and allowed to cool to r.t., where it was then diluted with CH₂Cl₂ and washed with ice-cold H₂O, 1% NaHCO₃, sat. NaHCO₃, and sat. NaCl soln. The org. layer was dried (MgSO₄) and concentrated to a colorless oil which was then dissolved in a minimal amount of CH₂Cl₂ and recrystallized by addition of Et₂O: β-lactose peracetate (58%). White, crystalline solid. M.p. 104 – 106 °C.

[0064] The β-lactose peracetate (1.78 g, 2.62 mmol), decan-1-ol (0.50 ml, 2.62 mmol), and InBr₃ (0.093 g, 0.262 mmol) were added to a 50 ml triple-walled resealable vessel (internally threaded with a Teflon plug), dissolved in ClCH₂CH₂Cl (3 – 4 ml), and irradiated in a 900 W Emerson-MW8992SB microwave oven (power level 6) for 2 min. The crude yellow oil was purified by FC (gradient AcOEt/hexanes 1:9 → 2:8 → 3:7 → 4:6): decyl β-lactoside peracetate (60%). White foam. M.p. 94 – 99 °C. ¹H-NMR (500 MHz, CDCl₃): 5.31 (d, J.3.2, 1 H); 5.16 (t, J.9.3, 1 H); 5.07 (dd, J.10.4, 7.9, 1 H); 4.92 (dd, J.10.4, 3.4, 1 H); 4.85 (dd, J.9.5, 8.0, 1 H); 4.49 – 4.38 (m, 3 H); 4.15 – 4.01 (m, 3 H); 3.87 – 3.72 (m, 3 H); 3.56 (ddd, J.9.8, 5.0, 1.9, 1 H); 3.41 (dt, J.9.6, 6.8, 1 H); 2.12 (s, J.2.9, 3 H); 2.09 (s, J.7.8, 3 H); 2.06 – 1.97 (m, 12 H); 1.93 (s, J.5.9, 3 H); 1.58 – 1.45 (m, 2 H); 1.33 – 1.16 (m, 14 H); 0.85 (t, J.6.9, 3 H). ¹³C-NMR (125 MHz, CDCl₃): 170.2; 170.2; 170.0; 169.9; 169.6; 169.4; 168.9; 101.0; 100.6; 76.3; 72.9; 72.6; 71.8; 71.0; 70.7; 70.2; 69.2; 66.7; 62.1; 60.8; 31.9; 29.6; 29.5; 29.4; 29.3; 29.3; 25.8; 22.7; 20.8; 20.8; 20.7; 20.6; 20.5; 14.1. ESI-MS (pos.): 815.1 (17, [M + K]⁺), 799.2 (99, [M + Na]⁺), 794.1 (53, [M + NH₄]⁺).

[0065] The decyl β-lactoside peracetate (2.93 g, 3.77 mmol) was dissolved in dry MeOH (30 ml) under Ar, and a 25% (wt./v) MeONa/MeOH soln. (0.5 ml) was added dropwise until the soln. reached pH 9 – 10. The mixture was stirred for 24 h (TLC monitoring) and then neutralized

by Dowex_50WX8–100 ion exchange resin. The mixture was filtered and the filtrate concentrated: decyl β -lactoside (72%). White solid. M.p. 140 – 160 °C (dec.). ^1H -NMR (500 MHz, (D_6) DMSO): 6.04 (s, 1 H); 5.84 – 5.31 (m, 4 H); 5.17 (dd, J.19.1, 7.5, 2 H); 4.73 (dt, J.6.6, 5.8, 2 H); 4.67 – 4.14 (m, 19 H); 3.99 (t, J.8.2, 1 H); 3.50 (dt, J. 3.6, 1.8, 1 H); 2.37 – 2.13 (m, 14 H); 1.85 (t, J.6.9, 3 H). ^{13}C -NMR (125 MHz, (D_6) DMSO): 103.8; 102.5; 80.8; 75.5; 75.0; 74.8; 73.2; 73.1; 70.6; 68.7; 68.1; 60.6; 60.4; 31.3; 29.3; 29.0; 29.0; 28.9; 28.7; 25.5; 22.1; 14.0. ESI-MS (pos.): 987.0 (100, $[2\text{ M} + \text{Na}]^+$), 964.9 (13, $[2\text{ M} + \text{H}]^+$), 505.4 (12, $[\text{M} + \text{Na}]^+$), 482.9 (10, $[\text{M} + \text{H}]^+$).

[0066] Microwave Procedure for Rhamnosides **6** – **8**. Rhamnose peracetate **5** (1.2 equiv.), alcohol (1 equiv.), and $\text{Sc}(\text{OTf})_3$ (1 equiv.), InBr_3 (0.1 equiv.), or $\text{BF}_3 \cdot \text{Et}_2\text{O}$ (5 equiv.) were dissolved in dry $\text{ClCH}_2\text{CH}_2\text{Cl}$ (1.5 ml) in a flame-dried triple-walled resealable vessel (internally threaded with a Teflon plug), and the vessel was microwave-irradiated (900 W Emerson MW8992SB) for 2 min on power level 6. The slightly yellow mixture was neutralized with sat. NaHCO_3 soln., the org. layer washed with H_2O , dried (MgSO_4), and concentrated, and the obtained oil purified by FC (20% AcOEt /hexanes).

[0067] Decyl 6-Dexoy- α -L-mannopyranoside Triacetate (**6**): Colorless oil. R_f (30% AcOEt /hexanes) 0.64. ^1H -NMR (500 MHz, CDCl_3): 5.28 (dd, J.10.1, 3.5, 1 H); 5.20 (dd, J.3.5, 1.7, 1 H); 5.03 (t, J.9.9, 1 H); 4.68 (d, J.1.5, 1 H); 3.84 (dq, J.9.9, 6.3, 1 H); 3.63 (dt, J.9.5, 6.8, 1 H); 3.39 (dt, J.9.6, 6.6, 1 H); 2.12 (s, 3 H); 2.02 (s, 3H); 1.96 (s, 3 H); 1.59 – 1.53 (m, 2 H); 1.35 – 1.21 (m, 14 H); 1.19 (d, J.6.3, 3 H); 0.86 (t, J.6.9, 3 H). ^{13}C -NMR (125 MHz, CDCl_3): 170.2; 170.0; 169.9; 97.4; 71.3; 70.0; 69.2; 68.2; 66.2; 31.9; 29.6; 29.5; 29.4; 29.3; 29.3; 26.1; 22.7; 20.9; 20.8; 20.7; 17.4; 14.1.

[0068] (1R)- and (1S)-1-Methylnonyl 6-Deoxy- α -L-mannopyranoside Triacetate (**7**; diastereoisomer mixture 1 : 1): Colorless oil. R_f (30% AcOEt /hexanes) 0.68. ^1H -NMR (500 MHz, CDCl_3): 5.28 (dd, J.10.1, 3.5, 1 H); 5.25 (dd, J.10.1, 3.5, 1 H); 5.15 – 5.11 (m, 2 H); 5.02 (t, J.9.9, 1 H); 5.01 (t, J.10.0, 1 H); 4.79 (d, J.1.7, 1 H); 4.77 (d, J.1.7, 1 H); 3.92 (dq, J.9.8, 6.3, 1 H); 3.89 (dq, J.9.8, 6.3, 1 H); 3.70 (dt, J.11.8, 6.0, 1 H); 3.64 (dt, J.12.4, 6.1, 1 H); 2.11 (s, 6 H); 2.01 (s, 3 H); 2.01 (s, 3 H); 1.95 (s, 6H); 1.60–1.44 (m, 2 H); 1.44 – 1.30 (m, 2H); 1.26 (dd, J.26.5, 8.0, 24 H); 1.16 (d, J.6.3, 9 H); 1.08 (d, J.6.1, 3 H); 0.84 (t, J.6.9, 3 H); 0.84 (t, J.7.0, 3 H). ^{13}C -NMR (125 MHz, CDCl_3): 170.2; 170.1; 170.0; 169.9; 169.9; 97.0; 94.9; 75.8; 73.1; 71.4;

71.2; 70.6; 70.4; 69.2; 69.2; 66.4; 66.2; 36.9; 36.2; 31.8; 31.8; 29.6; 29.5; 29.5; 29.5; 29.2; 29.2; 25.6; 25.3; 22.6; 21.1; 20.9; 20.8; 20.7; 18.9; 17.3; 17.3; 14.1.

[0069] Methyl (3R)- and (3S)-3-[(2,3,4-Tri-O-acetyl-6-deoxy- α -L-mannopyranosyl)oxy]decanoate (**8**; diastereoisomer mixture 1 : 1): Colorless oil. R_f (pair of diastereoisomers) 0.45 and 0.40. $^1\text{H-NMR}$ (500 MHz, CDCl_3): 5.21 (d, J.3.4, 1 H); 5.19 (d, J.3.4, 1 H); 5.11 (dd, J.3.4, 1.8, 1 H); 5.07 (dd, J. 3.4, 1.8, 1 H); 5.01 (t, J.9.9, 1 H); 4.99 (t, J.10.0, 1 H); 4.83 (d, J.1.5, 1 H); 4.80 (d, J.1.5, 1 H); 4.10 – 3.97 (m, 2 H); 3.94 – 3.82 (m, 2 H); 3.66 (s, 3 H); 3.65 (s, 3 H); 2.54 (dd, J.15.3, 8.1, 1 H); 2.50 (dd, J.15.5, 7.5, 1 H); 2.44 (dd, J.15.4, 6.4, 1 H); 2.43 (dd, J.15.4, 6.9, 1 H); 2.10 (d, J.2.8, 6 H); 2.00 (d, J.3.0, 6 H); 1.93 (d, J.1.9, 6 H); 1.63 – 1.40 (m, 4 H); 1.36 – 1.17 (m, 16 H); 1.16 (d, J.6.3, 1 H); 1.15 (d, J.6.2, 1 H); 0.83 (td, J.6.9, 3.5, 6 H). $^{13}\text{C-NMR}$ (125 MHz, CDCl_3): 171.7; 171.6; 170.1; 170.0; 169.9; 169.9; 169.9; 97.5; 95.9; 76.3; 74.9; 71.1; 70.3; 70.2; 69.1; 69.0; 66.7; 66.6; 51.7; 51.6; 39.9; 39.3; 35.0; 33.3; 31.7; 31.7; 29.4; 29.4; 29.1; 29.1; 25.1; 24.7; 22.6; 22.6; 20.9; 20.9; 20.8; 20.7; 17.2; 17.2; 14.0.

[0070] Conventional Reflux Procedure for Rhamnosides. To a soln. of rhamnose peracetate **5** (2.2 equiv.) in dry MeCN, the alcohol (1 equiv.) (**2**, **3** or benzyl ester of **4**) and either $\text{Bi}(\text{OTf})_3$ (0.10 equiv.) or InBr_3 (0.10 equiv.) were added. The mixture was refluxed under a Liebig condenser for 2.5 h and then allowed to cool to r.t. For $\text{Bi}(\text{OTf})_3$, the yellow-brown mixture was diluted with CH_2Cl_2 , Celite_® was added, the mixture filtered, and the filtrate concentrated to a yellow-brown syrup. For InBr_3 , the yellow mixture was diluted with CH_2Cl_2 and neutralized with sat. NaHCO_3 soln., and the org. layer washed with H_2O , dried (MgSO_4), and concentrated. Purification was achieved by FC (gradient hexanes/ AcOEt 0 $\rightarrow$ 20%). Yields of 89%, 83%, 38% for InBr_3 and 91%, 89% and 60% for $\text{Bi}(\text{OTf})_3$ for alcohols **2**, **3** and benzyl ester of **4**, respectively.

[0071] Phenylmethyl (3R)- and (3S)-3-[(2,3,4-Tri-O-acetyl-6-deoxy- α -L-mannopyranosyl)oxy]decanoate (diastereoisomer mixture 45 : 55): Colorless oil. R_f (30% AcOEt /hexanes) 0.55. $^1\text{H-NMR}$ (500 MHz, CDCl_3): 7.36 – 7.27 (m, 10 H); 5.23 (ddd, J.10.1, 3.4, 1.0, 2 H); 5.14 (dt, J.4.4, 2.2, 1 H); 5.13 – 5.10 (m, 5 H); 5.02 (td, J.10.0, 5.9, 2 H); 4.87 (d, J.1.6, 1 H); 4.83 (d, J.1.6, 1 H); 4.14 – 4.02 (m, 2 H); 3.95 – 3.86 (m, 2 H); 2.66 – 2.46 (m, 4 H); 2.12 (d, J.5.9, 6 H); 2.04 – 1.99 (m, 6H); 1.96 (d, J.1.5, 6 H); 1.63 – 1.43 (m, 4 H); 1.37 – 1.19 (m, 23 H); 1.18 (d, J.6.3, 3 H); 1.15 (d, J.6.3, 3 H); 0.85 (td, J.6.9, 3.7, 6 H). $^{13}\text{C-NMR}$ (125

MHz, CDCl₃): 171.1; 170.9; 170.1; 170.0; 169.9; 135.7; 135.7; 128.5; 128.5; 128.4; 128.2; 128.2; 97.4; 96.2; 76.1; 75.1; 71.1; 70.3; 70.2; 69.1; 69.1; 66.7; 66.7; 66.5; 66.4; 40.2; 39.5; 35.0; 33.4; 31.7; 29.5; 29.4; 29.1; 29.1; 25.1; 24.7; 22.6; 22.6; 20.9; 20.8; 20.7; 17.3; 14.1.

[0072] (3R)- and (3S)-3-[(2,3,4-Tri-O-acetyl-6-deoxy- α -L-mannopyranosyl)oxy]decanoic Acid (diastereomeric mixture; (R)-11 and (S)-11, resp.). To a soln. of 10 (8.57 g, 15.6 mmol) in dry THF (100 ml) at r.t., a small amount of 10% (wt.) Pd/C was added under Ar. By means of a balloon, the flask was filled with H₂ gas (1 atm) and the mixture stirred vigorously at r.t. for 24 h. Then the mixture was purged with Ar, diluted with CH₂Cl₂, and filtered through Celite, the filtrate was concentrated, and the resulting oil was purified by FC (Et₂O/hexanes 1:1 with 1% AcOH): (R)-11 (38%) and (S)-11 (33%).

[0073] Data of (R)-11: Colorless oil. [a]_D = -30.6 (c=1.0, CHCl₃). R_f (Et₂O/hexanes 1:1 with 1% (v/v) AcOH) 0.26. ¹H-NMR (400 MHz, CDCl₃): 5.24 (dd, J.10.1, 3.5, 1 H); 5.12 (dd, J.3.4, 1.8, 1 H); 5.03 (t, J.9.9, 1 H); 4.89 (d, J.1.8, 1 H); 4.04 (dq, J.11.7, 5.9, 1 H); 3.93 (dq, J.9.8, 6.3, 1 H); 2.57 (dd, J.15.8, 7.5, 1 H); 2.49 (dd, J.15.8, 5.3, 1 H); 2.11 (s, 3 H); 2.03 (s, 3H); 1.96 (s, 3 H); 1.65 – 1.50 (m, 2 H); 1.32 – 1.22 (m, 10 H); 1.18 (d, J.6.3, 3 H); 0.89 – 0.84 (m, 3H). ¹³C-NMR (100 MHz, CDCl₃): 176.2; 170.2; 170.1; 170.1; 97.5; 76.2; 71.1; 70.3; 69.1; 66.8; 39.3; 35.0; 31.7; 29.4; 29.1; 25.1; 22.6; 20.9; 20.8; 20.7; 20.7; 17.3; 14.0.

[0074] Data of (S)-11: Clear oil. [a]_D = -47.9 (c=1.0, CHCl₃); R_f (Et₂O/hexanes 1:1 with 1% (v/v) AcOH) 0.38. ¹H-NMR (400 MHz, CDCl₃): 5.23 (dd, J.10.1, 3.4, 1 H); 5.14 (dd, J.3.4, 1.8, 1 H); 5.02 (t, J.9.9, 1 H); 4.82 (d, J.1.7, 1 H); 4.07 (dq, J.7.5, 5.9, 1 H); 3.93 (dq, J.9.9, 6.3, 1 H); 2.63 (dd, J.15.9, 7.6, 1 H); 2.52 (dd, J.15.9, 4.8, 1 H); 2.12 (s, 3 H); 2.02 (s, 3H); 1.96 (s, 3H); 1.52 (ddd, J.23.0, 14.2, 5.3, 2 H); 1.32 – 1.21 (m, 10 H); 1.15 (d, J.6.3, 3 H); 0.87 – 0.82 (m, 3H). ¹³C-NMR (100 MHz, CDCl₃): 176.7; 170.2; 170.1; 170.0; 96.4; 75.1; 71.1; 70.3; 69.1; 66.8; 39.9; 33.6; 31.7; 29.5; 29.1; 24.8; 22.6; 20.9; 20.8; 20.7; 17.2; 14.0.

[0075] (3R)- and (3S)-3-(6-Deoxy- α -L-mannopyranosyloxy)decanoic Acid (diastereomeric mixture; (R)-1 and (S)-1, resp.). To a soln. of (R)-11 (5.77g, 12.5 mmol) in dry MeOH (50 ml) at r.t., MeONa was added while stirring to achieve a pH 9 – 10 (monitoring by a drop of the mixture onto a moistened pH-indicator strip). The mixture was stirred at r.t. for 3.5 h and then quenched with Dowex H resin. The resin was removed by filtration and the filtrate

concentrated to an oil. No further purification was required. However, redissolving of the product in a minimal amount of hexanes, followed by filtration, was occasionally required to remove residual Na salts: (R)-1 (99%). Colorless oil. $[\alpha]_D = -34.8$ ($c=1.0$, MeOH). R_f (10% MeOH/ CH_2Cl_2 with 1% (v/v) AcOH) 0.20. $^1\text{H-NMR}$ (400 MHz, CD_3OD): 4.75 (d, J.1.7, 1 H); 3.96 – 3.89 (m, 1 H); 3.65 (dd, J.3.4, 1.7, 1 H); 3.61 – 3.53 (m, 1 H); 3.51 (dd, J.9.5, 3.4, 1 H); 3.29 – 3.24 (m, 1 H); 2.34 (qd, J.15.0, 6.4, 2 H); 1.54 – 1.43 (m, 2 H); 1.26 – 1.17 (m, 10 H); 1.14 (d, J.6.3, 3 H); 0.80 (dd, J.7.9, 6.0, 3 H). $^{13}\text{C-NMR}$ (100 MHz, CD_3OD): 176.2; 101.6; 76.9; 73.9; 72.7; 72.4; 70.2; 41.2; 36.4; 33.0; 30.7; 30.3; 26.3; 23.7; 17.9; 14.4. ESI-MS (neg.): 334.1 (12, M $^-$), 333.1 (99, [M – H] $^-$).

[0076] Glycolipid (S)-1 was obtained in the same fashion: Yield 99%. Colorless oil. $[\alpha]_D = -47.0$ ($c=1.0$, MeOH). R_f (10% MeOH/ CH_2Cl_2 with 1% (v/v) AcOH) 0.25. $^1\text{H-NMR}$ (400 MHz, CD_3OD): 4.66 (d, J. 1.7, 1 H); 3.93 (dq, J.7.5, 5.7, 1 H); 3.62 (dd, J.3.4, 1.7, 1 H); 3.58 – 3.45 (m, 2 H); 3.20 (t, J.9.5, 1 H); 2.33 (ddd, J.20.4, 14.8, 6.6, 2 H); 1.42 (dt, J.9.1, 6.2, 2 H); 1.21 – 1.13 (m, 10 H); 1.09 (d, J.6.2, 3 H); 0.77 – 0.73 (m, 3H). $^{13}\text{C-NMR}$ (100 MHz, CD_3OD): 176.5; 100.3; 75.9; 74.0; 72.7; 72.3; 70.1; 42.2; 34.5; 33.0; 30.7; 30.3; 25.9; 23.7; 17.9; 14.4. ESI-MS (neg.): 334.1 (12, M $^-$), 333.1 (99, [M – H] $^-$).

[0077] *Synthesis of peracetylated C₁₀ rhamnosides via microwave-assisted glycosylation.* In a flame-dried microwave bomb, rhamnose peracetate and methyl 3-hydroxydecanoate were dissolved in $\text{ClCH}_2\text{CH}_2\text{Cl}$. The glycosylation promoter was added and the vessel was microwave-irradiated for 1-3 minutes. The slightly yellow reaction mixture was neutralized using saturated NaHCO_3 and the layers were separated. The organic layers were washed with H_2O and dried over MgSO_4 , filtered, and concentrated via rotary evaporation. The crude product was purified by column chromatography to give the products as colorless syrups. The yield of glycosylated products were 16%, 34% and 33% for $\text{Sc}(\text{OTf})_3$, InBr_3 and $\text{BF}_3 \cdot \text{OEt}_2$ glycosylation promoters, respectively.

[0078] The foregoing discussion of the invention has been presented for purposes of illustration and description. The foregoing is not intended to limit the invention to the form or forms disclosed herein. Although the description of the invention has included description of one or more embodiments and certain variations and modifications, other variations and modifications are within the scope of the invention, e.g., as may be within the skill and

knowledge of those in the art, after understanding the present disclosure. It is intended to obtain rights which include alternative embodiments to the extent permitted, including alternate, interchangeable and/or equivalent structures, functions, ranges or steps to those claimed, whether or not such alternate, interchangeable and/or equivalent structures, functions, ranges or steps are disclosed herein, and without intending to publicly dedicate any patentable subject matter.

What is Claimed is:

1. A method for producing a surfactant, said method comprising contacting a hydrophilic compound with a hydrophobic compound in the presence of a catalytic amount of a bismuth-based promoter under conditions sufficient to form a covalent bond between said hydrophilic compound and said hydrophobic compound to produce a surfactant, wherein said hydrophobic compound comprises a functional group selected from the group consisting of an amine group, a hydroxyl group and a thiol group.
2. The method of Claim 1, wherein said bismuth-based promoter comprises bismuth trifluoromethanesulfonate, bismuth halide, or a mixture thereof.
3. The method Claim 1, wherein the amount of bismuth-based promoter is about 0.25 equivalent or less.
4. The method of Claim 1, wherein the amount of bismuth-based promoter is about 0.1 equivalent or less.
5. The method of Claim 1, wherein said hydrophilic compound is a carbohydrate.
6. The method of Claim 5, wherein said carbohydrate comprises a hydroxy protecting group.
7. The method of Claim 6, wherein said hydroxyl protecting group is an ester.
8. The method of Claim 1, wherein said hydrophobic compound is a hydrocarbon compound of the formula R^x-X , wherein R^x is a hydrocarbon and X is $-OH$, $-NH_2$, or $-SH$.
9. The method of Claim 8, wherein R^x is a C_6-C_{30} hydrocarbon.
10. The method of Claim 8, wherein R^x is a C_6-C_{18} hydrocarbon.
11. A method for producing a glycolipid, said method comprising contacting a carbohydrate with a lipid in the presence of a catalytic amount of a bismuth-based glycosylation promoter under conditions sufficient to produce a glycolipid, wherein said lipid comprises a glycosylation functional group selected from the group consisting of an amine group, a hydroxyl group and a thiol group, and wherein said lipid is glycosylated at said glycosylation functional group.

12. The method of Claim 11, wherein said bismuth-based glycosylation promoter comprises bismuth trifluoromethanesulfonate, bismuth halide, or a mixture thereof.

13. The method Claim 11, wherein the amount of bismuth-based glycosylation promoter is about 0.25 equivalent or less.

14. The method of Claim 11, wherein the amount of bismuth-based glycosylation promoter is about 0.1 equivalent or less.

15. The method of Claim 11, wherein said carbohydrate comprises a hydroxy protecting group.

16. The method of Claim 15, wherein said hydroxyl protecting group is an ester.

17. The method of Claim 11, wherein said lipid comprises a C₆-C₃₀ alkyl chain.

18. The method of claim 17, wherein said lipid comprises a C₆-C₁₈ alkyl chain.

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US 2013/062575

A. CLASSIFICATION OF SUBJECT MATTER		C07H 15/02 (2006.01) C07F 9/94 (2006.01) C07H 13/06 (2006.01) C08B 37/00 (2006.01) B01J 23/00 (2006.01)										
According to International Patent Classification (IPC) or to both national classification and IPC												
B. FIELDS SEARCHED												
Minimum documentation searched (classification system followed by classification symbols)												
C07H 15/02, C07F 9/94, C07H 13/06, C08B 37/00, B01J 23/00, C07H 15/00, 15/18, B01F 17/56												
Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched												
Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)												
VINITI, DWPI, EAPATIS, Espacenet, PAJ, USPTO, CIPO, DEPATISnet, Patentscope, Information Retrieval System of FIPS (http://www1.fips.ru/wps/portal/Registers/)												
C. DOCUMENTS CONSIDERED TO BE RELEVANT												
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.										
X Y	US 2003/0045706 A1 (JEAN-CLAUDE YVIN et al.) 06.03.2003, examples 16-18, claims, reaction scheme I	11-12, 15-18 1-10, 13-14										
Y	JP 2008222618 A (NOGUCHI INST) 25.09.2008, examples, claims	13-14										
Y	KIYOSHI, Ikeda et al. Glycosylation of sialyl acetates with a novel catalyst combination: Bismuth triflate and BF ₃ ·OEt ₂ system. Bioorganic & Medicinal Chemistry, Volume 11, Issue 14, 17 July 2003, pp. 3073-3076, abstract	1-10										
Y	SALAGER, Jean-Louis. Surfactants Types and Uses. Universidad de Los Andes, Merida-Venezuela, Version #2, English translation, 15.12.2002, 49, pp. 2, 3-4, 28, 32-34 [online] Retrieved from the Internet: <URL: http://www.nanoparticles.org/pdf/Salager-E300A.pdf >	1-10										
☒ Further documents are listed in the continuation of Box C. ☐ See patent family annex.												
* Special categories of cited documents: <table border="0"> <tr> <td>“A” document defining the general state of the art which is not considered to be of particular relevance</td> <td>“T” later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention</td> </tr> <tr> <td>“E” earlier document but published on or after the international filing date</td> <td>“X” document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone</td> </tr> <tr> <td>“L” document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)</td> <td>“Y” document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art</td> </tr> <tr> <td>“O” document referring to an oral disclosure, use, exhibition or other means</td> <td>“&” document member of the same patent family</td> </tr> <tr> <td>“P” document published prior to the international filing date but later than the priority date claimed</td> <td></td> </tr> </table>			“A” document defining the general state of the art which is not considered to be of particular relevance	“T” later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention	“E” earlier document but published on or after the international filing date	“X” document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone	“L” document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)	“Y” document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art	“O” document referring to an oral disclosure, use, exhibition or other means	“&” document member of the same patent family	“P” document published prior to the international filing date but later than the priority date claimed	
“A” document defining the general state of the art which is not considered to be of particular relevance	“T” later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention											
“E” earlier document but published on or after the international filing date	“X” document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone											
“L” document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)	“Y” document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art											
“O” document referring to an oral disclosure, use, exhibition or other means	“&” document member of the same patent family											
“P” document published prior to the international filing date but later than the priority date claimed												
Date of the actual completion of the international search		Date of mailing of the international search report										
22 November 2013 (22.11.2013)		27 February 2014 (27.02.2014)										
Name and mailing address of the ISA/ FIPS Russia, 123995, Moscow, G-59, GSP-5, Berezhkovskaya nab., 30-1		Authorized officer										
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		Telephone No. (495)531-64-81										

INTERNATIONAL SEARCH REPORT

International application No.

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Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. ☐ Claims Nos.:
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:

3. ☐ Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.
2. ☐ As all searchable claims could be searched without effort justifying additional fees, this Authority did not invite payment of additional fees.
3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:
4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest

- ☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.
- ☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.
- ☐ No protest accompanied the payment of additional search fees.

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US 2013/062575

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	IVANOVA E.A. et al. Sintez galaktozosoderzhaschikh amfifilov. Vestnik MITKHT, 2010, t. 5, № 5, pp. 65-70 (66)	1-10
Y	COSS, Clifford Scott et al. Synthetic Method for the Development of Monorhamnolipids. FASEB J., April 6, 2010, 24:689	1-10
Y	LEONARD, Nicolas M. et al. Application of bismuth (III) compounds in organic synthesis. Tetrahedron, 2002, 58, pp. 8373-8397, especially, pp.8386-8391	1-10