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Wertz et al.

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(54) FLAME RETARDANT LEVULINIC ACID-BASED COMPOUNDS

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(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 394 days.

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(65) **Prior Publication Data**

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Related U.S. Application Data

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(51) **Int. Cl.**
C09K 21/06 (2006.01)
C08G 85/00 (2006.01)
(Continued)

(52) **U.S. Cl.**
CPC ***C09K 21/06*** (2013.01); ***C08G 59/304*** (2013.01); ***C08G 64/0258*** (2013.01);
(Continued)

(58) **Field of Classification Search**
CPC C08K 5/006; C08K 5/5313; C08K 5/5317; C09K 21/12
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

3,267,070 A * 8/1966 Dickerson C08L 25/04
524/774
3,399,171 A 8/1968 Vogt et al.
(Continued)

FOREIGN PATENT DOCUMENTS

EP 1905776 A1 * 4/2008 .... C07F 9/301
JP 57159088 A * 10/1982
(Continued)

OTHER PUBLICATIONS

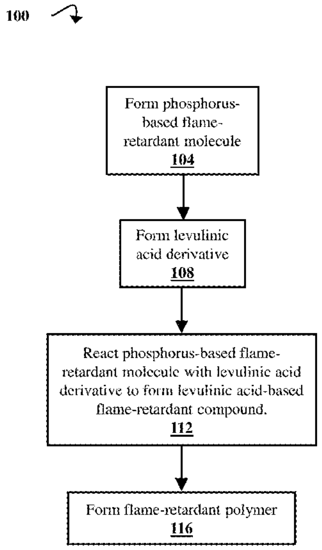
Machine translation of PL 136454 (1986, 3 pages).*
(Continued)

Primary Examiner — Brieann R Johnston
(74) *Attorney, Agent, or Firm* — Rachel M. Yadlosky

(57) ABSTRACT

A flame retardant levulinic acid-based compound, a process for forming a levulinic acid-based flame retardant polymer, and an article of manufacture comprising a material that contains a flame retardant levulinic acid-based polymer are disclosed. The flame retardant levulinic acid-based compound has variable moieties, which include phenyl-substituted and/or R functionalized flame retardant groups. The process for forming the flame retardant polymer includes forming a phosphorus-based flame retardant molecule, forming a levulinic acid derivative, chemically reacting the phosphorus-based flame retardant molecule and the levulinic acid derivative to form a flame retardant levulinic acid-based compound, and incorporating the levulinic acid-based flame retardant compound into a polymer to form the flame retardant polymer.

18 Claims, 24 Drawing Sheets



(51) **Int. Cl.**

C08K 5/51	(2006.01)
C09K 21/12	(2006.01)
C08K 5/5313	(2006.01)
C08G 59/30	(2006.01)
C08K 5/5317	(2006.01)
C08G 64/02	(2006.01)
C08L 85/02	(2006.01)
C08K 5/00	(2006.01)

(52) **U.S. Cl.**

CPC ***C08G 85/004*** (2013.01); ***C08K 5/51*** (2013.01); ***C08K 5/5313*** (2013.01); ***C08K 5/5317*** (2013.01); ***C08L 85/02*** (2013.01); ***C09K 21/12*** (2013.01); *C08K 5/0066* (2013.01)

(56) **References Cited**

U.S. PATENT DOCUMENTS

2008/0038528 A1* 2/2008 Paul C09J 107/00
428/500
2008/0214708 A1 9/2008 Bauer et al.
2010/0124583 A1 5/2010 Medoff
2015/0148499 A1 5/2015 Boday et al.
2015/0225510 A1 8/2015 Boday et al.
2015/0225511 A1 8/2015 Boday et al.
2016/0237352 A1 8/2016 Boday et al.
2016/0237353 A1 8/2016 Boday et al.
2018/0346619 A1* 12/2018 Czaplewski C09J 143/02
2019/0106630 A1 4/2019 Wertz et al.

FOREIGN PATENT DOCUMENTS

KR 20160118753 A * 10/2016
PL 136454 B1 * 2/1986

OTHER PUBLICATIONS

Machine translation of EP 1905776 (2008, 26 pages).*
SciFinder information for U.S. Pat. No. 3,267,070.*
SciFinder substances for U.S. Pat. No. 3,267,070.*
Yan (Application of poly(diphenolic acid-phenyl phosphate)-based layer by layer nanocoating in flame retardant ramie fabrics, Journal of Applied Polymer Science, 2017, 13 pages).*
Liu (Design, Synthesis, and Application of Novel Flame Retardants Derived From Biomass, BioResources, 7(4), 2012, pp. 4914-4925).*
SciFinder Abstract of JP 57159088 (1982).*
Machine translation of KR 20160118753 (2016, 8 pages).*
Green et al., "Dimethyl Acetals", Protective Groups in Organic Synthesis, 1999, printed Jun. 29, 2017, 4 pages.
List of IBM Patents or Patent Applications Treated as Related, Jan. 20, 2021, 2 pgs.
Liu et al., "Design, Synthesis, And Application Of Novel Flame Retardants Derived From Biomass", BioResources, 2012, pp. 4914-4925.

* cited by examiner

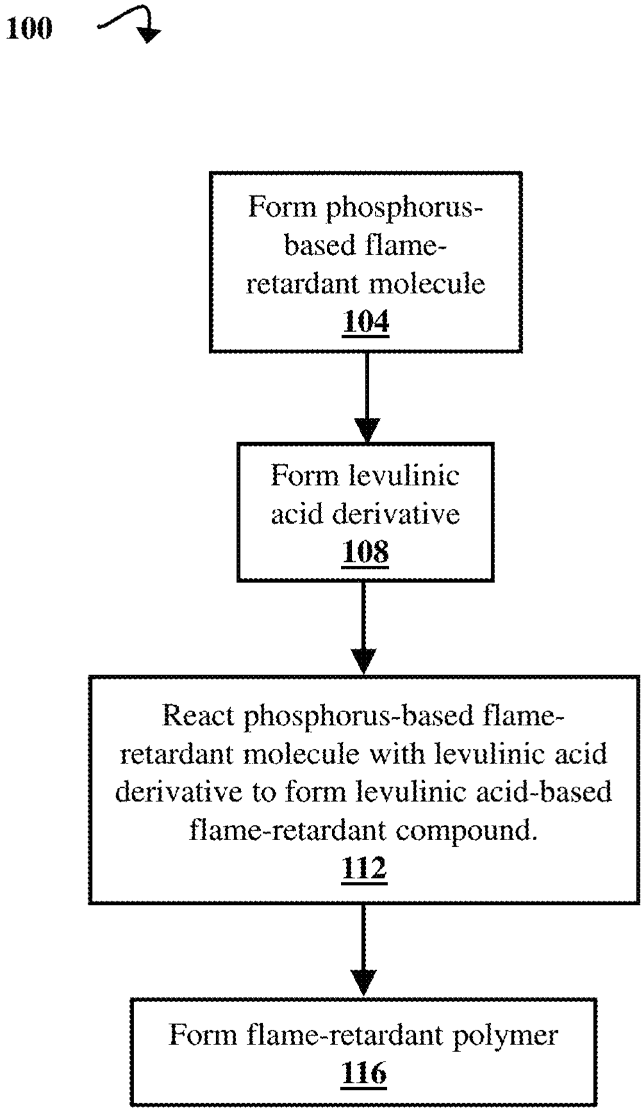

100
Form phosphorus-based flame-retardant molecule
104
Form levulinic acid derivative
108
React phosphorus-based flame-retardant molecule with levulinic acid derivative to form levulinic acid-based flame-retardant compound.
112
Form flame-retardant polymer
116

FIG. 1

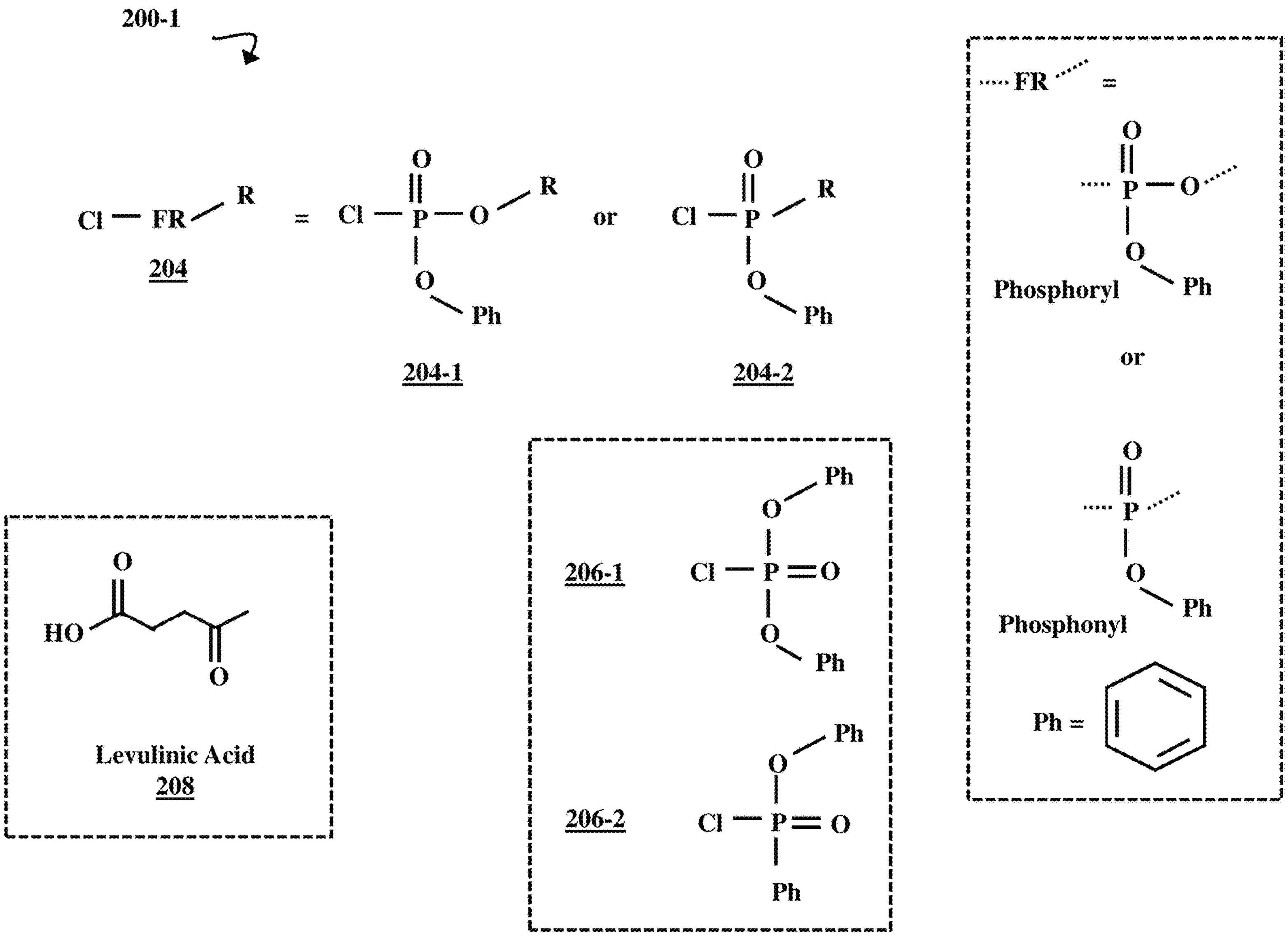
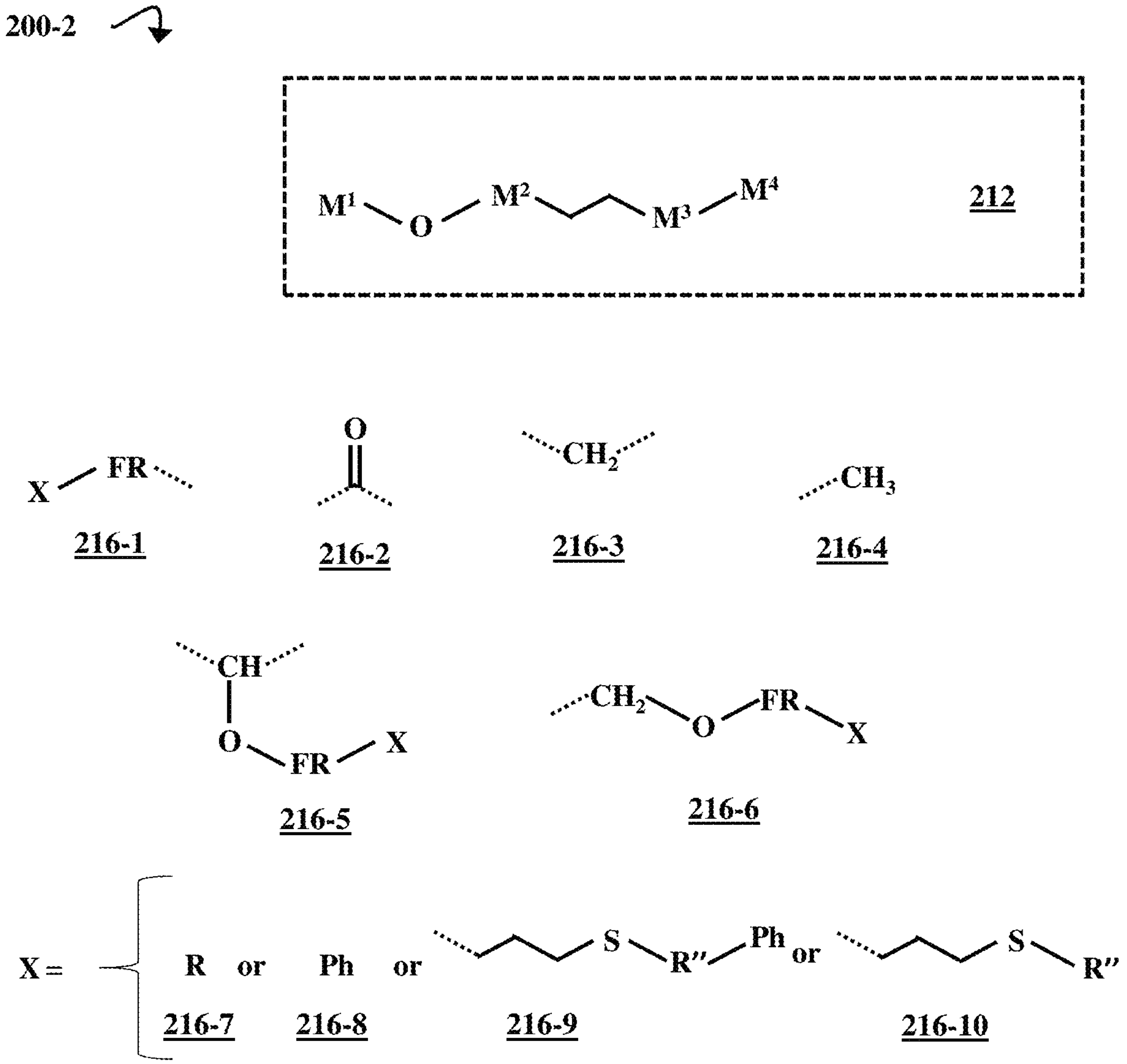

200-1
Cl — FR — R
204
=
204-1
or
204-2
Phosphoryl
or
Phosphonyl
Ph =
206-1
206-2
Levulinic Acid
208

FIG. 2A



M^1 = 216-1 with X = 216-7, 216-8, 216-9, or 216-10

M^2 = 216-2 or 216-3

M^3 = 216-3 or 216-5 with X = 216-7, 216-8, 216-9, or 216-10

M^4 = 216-4 or 216-6 with X = 216-7, 216-8, 216-9, or 216-10

FIG. 2B

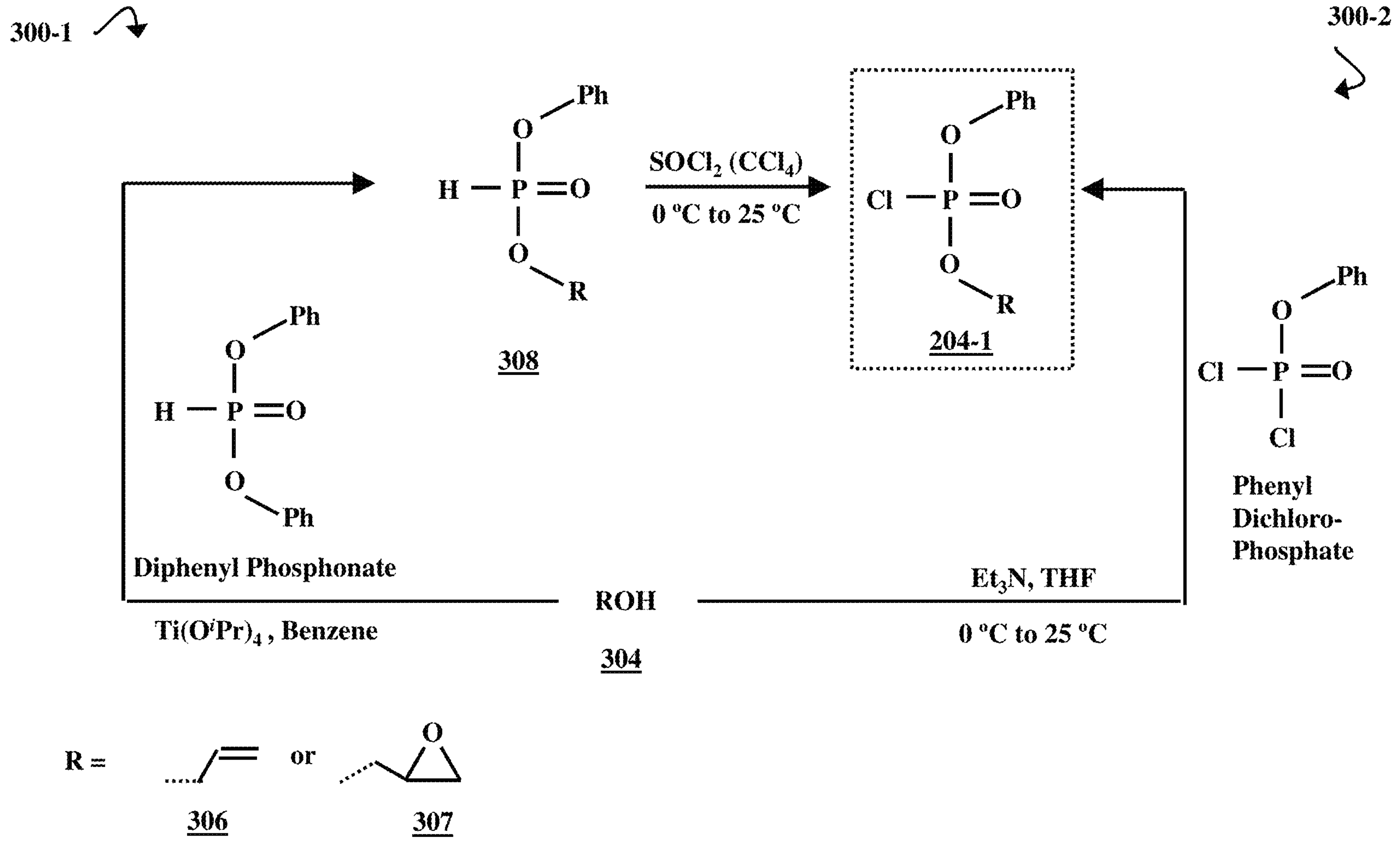

300-1
300-2
Ph
O
H
P
O
O
R
308
SOCl$_2$ (CCl$_4$)
0 °C to 25 °C
Ph
O
Cl
P
O
O
R
204-1
Ph
O
H
P
O
O
Ph
Diphenyl Phosphonate
Ph
O
Cl
P
O
Cl
Phenyl Dichloro-Phosphate
ROH
304
Ti(O^{i}Pr)$_4$, Benzene
Et$_3$N, THF
0 °C to 25 °C
R =
or
O
306
307

FIG. 3A

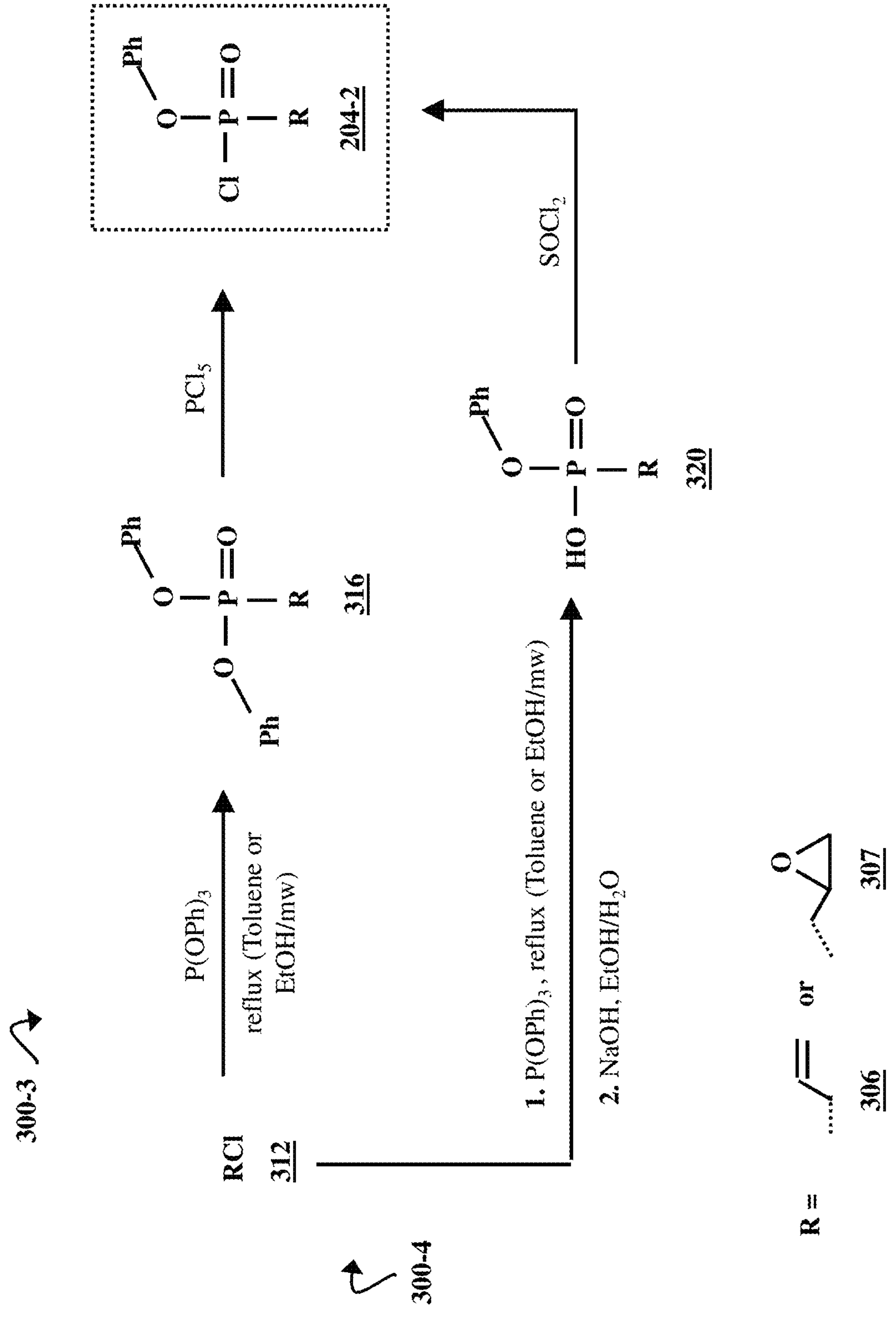

300-3
300-4
RCl
312
$P(OPh)_3$
reflux (Toluene or EtOH/mw)
Ph
O
P
O
R
316
PCl_5
Cl
204-2
1. $P(OPh)_3$, reflux (Toluene or EtOH/mw)
2. NaOH, EtOH/H_2O
HO
320
$SOCl_2$
R =
306
or
O
307

FIG. 3B

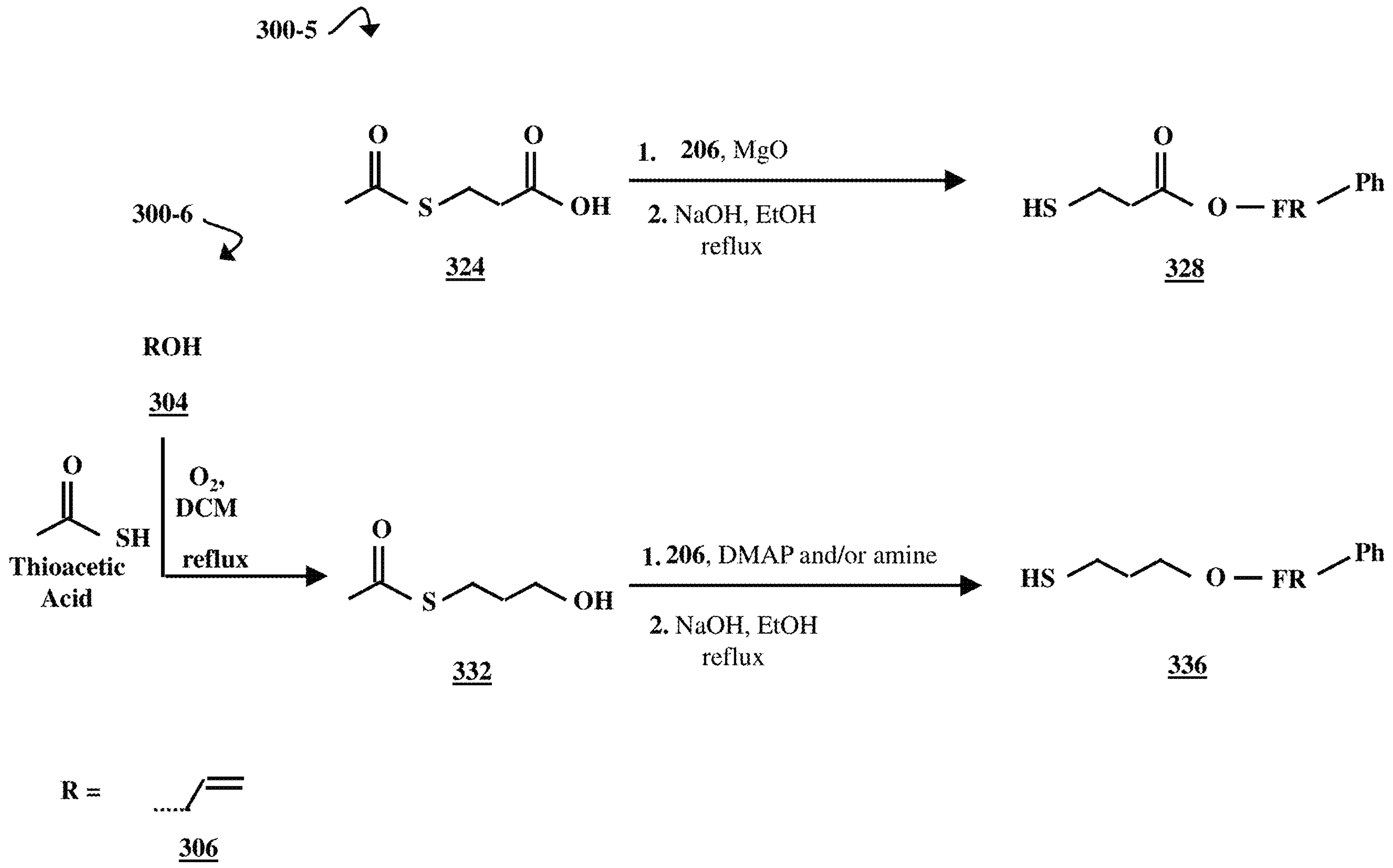

300-5
300-6
O
S
OH
324
1. 206, MgO
2. NaOH, EtOH
reflux
HS
O — FR
Ph
328
ROH
304
Thioacetic
Acid
SH
O$_2$,
DCM
reflux
332
1. 206, DMAP and/or amine
2. NaOH, EtOH
reflux
336
R =
306

FIG. 3C

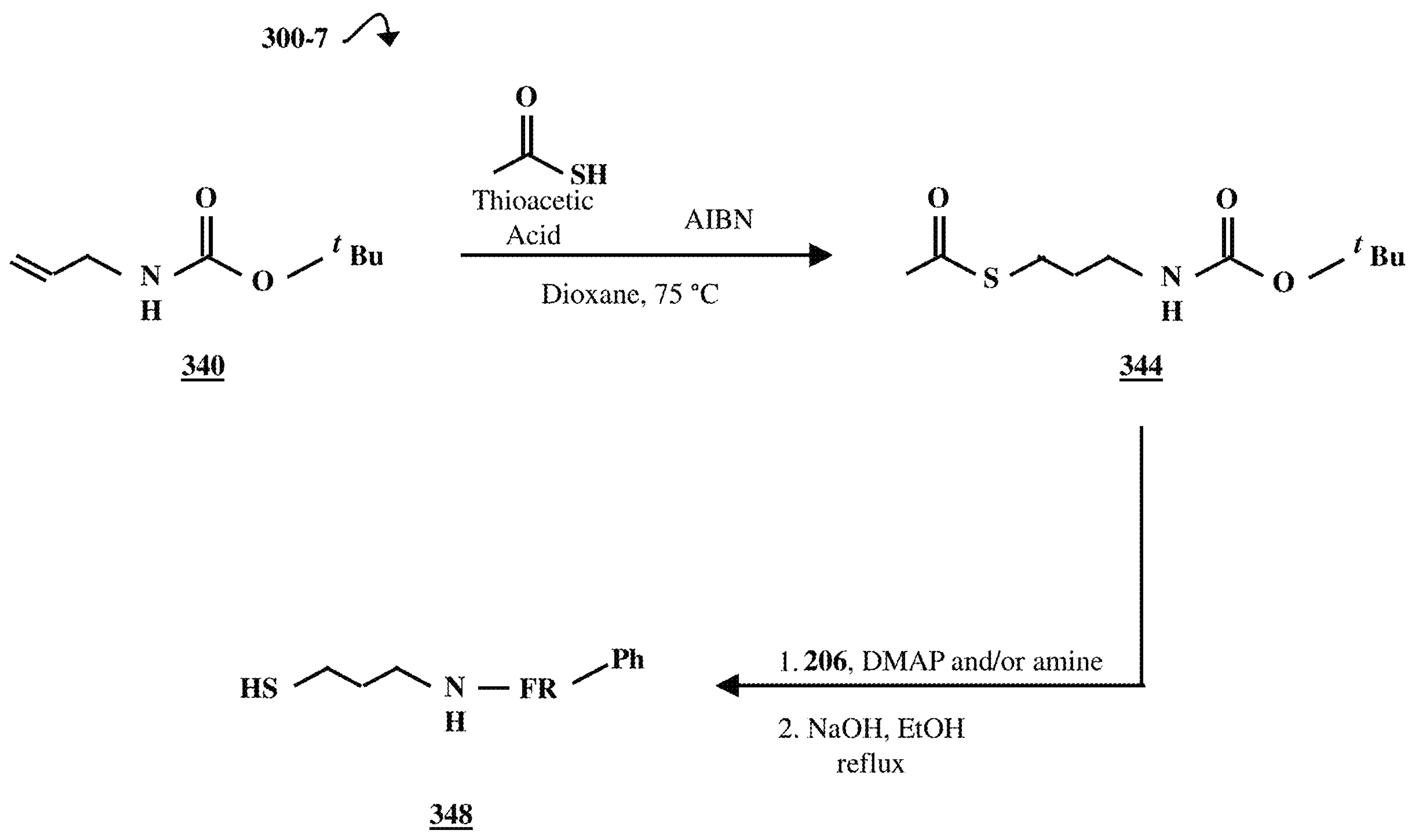
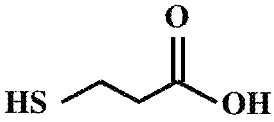

300-7
O
N
H
O
^{t}Bu
340
O
SH
Thioacetic Acid
AIBN
Dioxane, 75 °C
O
S
O
N
H
O
^{t}Bu
344
1. 206, DMAP and/or amine
2. NaOH, EtOH reflux
HS
N
H
FR
Ph
348

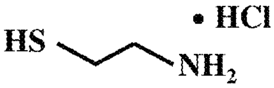
FIG. 3D

302



352 3-Mercaptopropionate

356 2-Mercaptoethanol



360 Cysteamine HCl

FIG. 3E

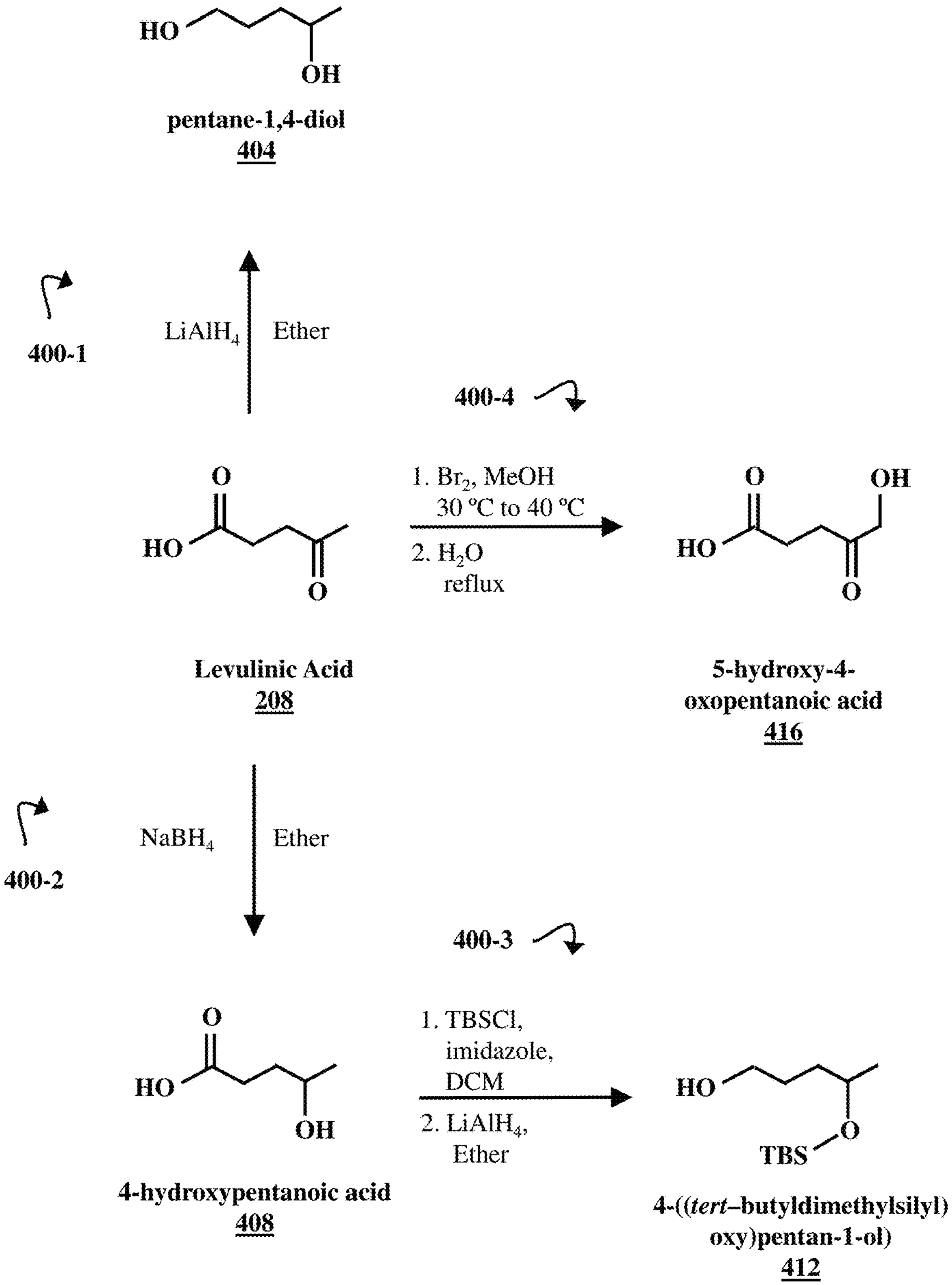

HO
OH
pentane-1,4-diol
404
400-1
$LiAlH_4$
Ether
400-4
O
HO
O
Levulinic Acid
208
1. Br_2, MeOH
30 °C to 40 °C
2. H_2O
reflux
O
OH
HO
O
5-hydroxy-4-oxopentanoic acid
416
400-2
$NaBH_4$
Ether
400-3
O
HO
OH
4-hydroxypentanoic acid
408
1. TBSCl,
imidazole,
DCM
2. $LiAlH_4$,
Ether
HO
O
TBS
4-((*tert*–butyldimethylsilyl)
oxy)pentan-1-ol)
412

FIG. 4A

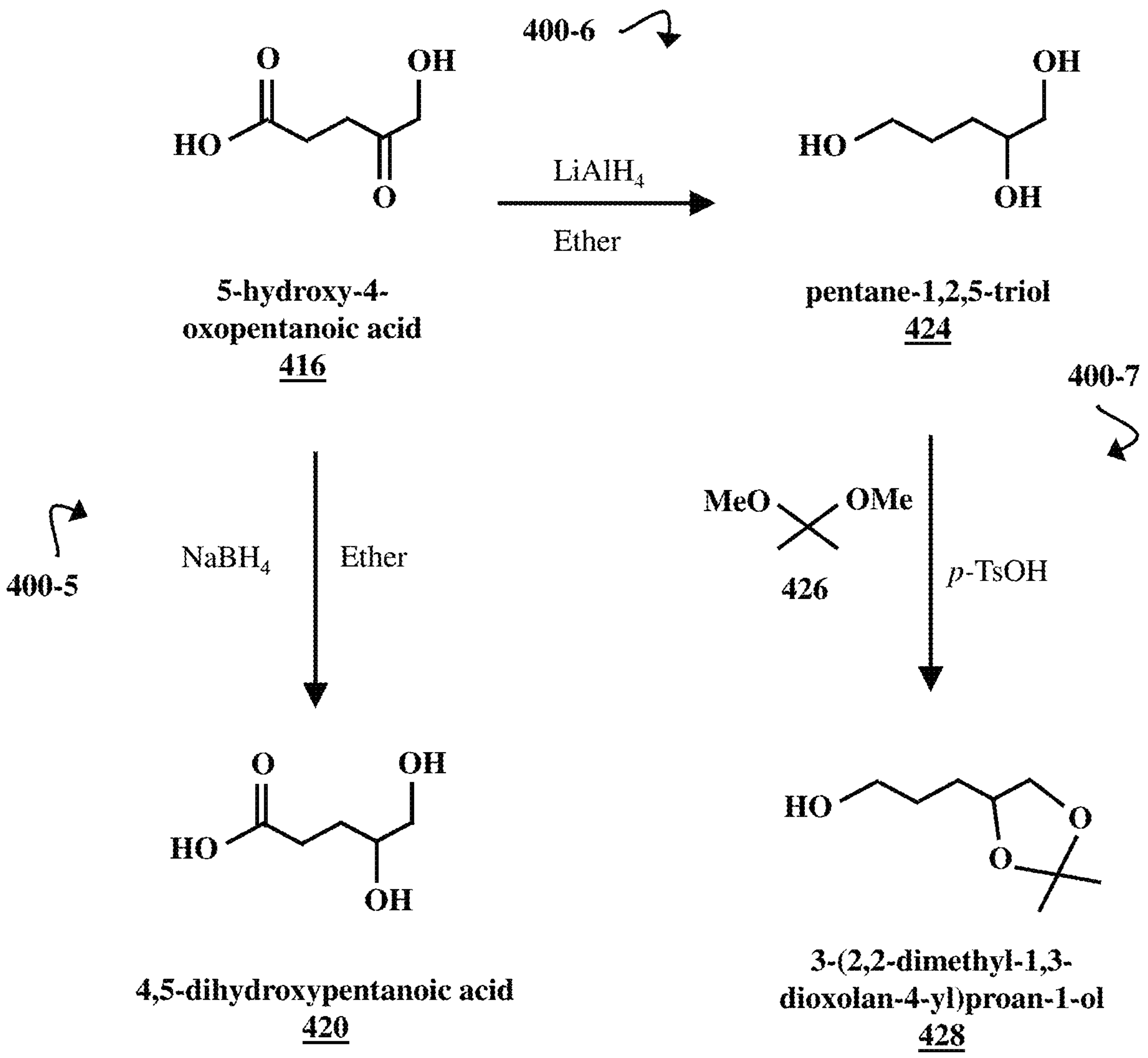

400-6
LiAlH4
Ether
5-hydroxy-4-oxopentanoic acid
416
pentane-1,2,5-triol
424
400-7
400-5
NaBH4
Ether
MeO
OMe
426
p-TsOH
4,5-dihydroxypentanoic acid
420
3-(2,2-dimethyl-1,3-dioxolan-4-yl)proan-1-ol
428

FIG. 4B

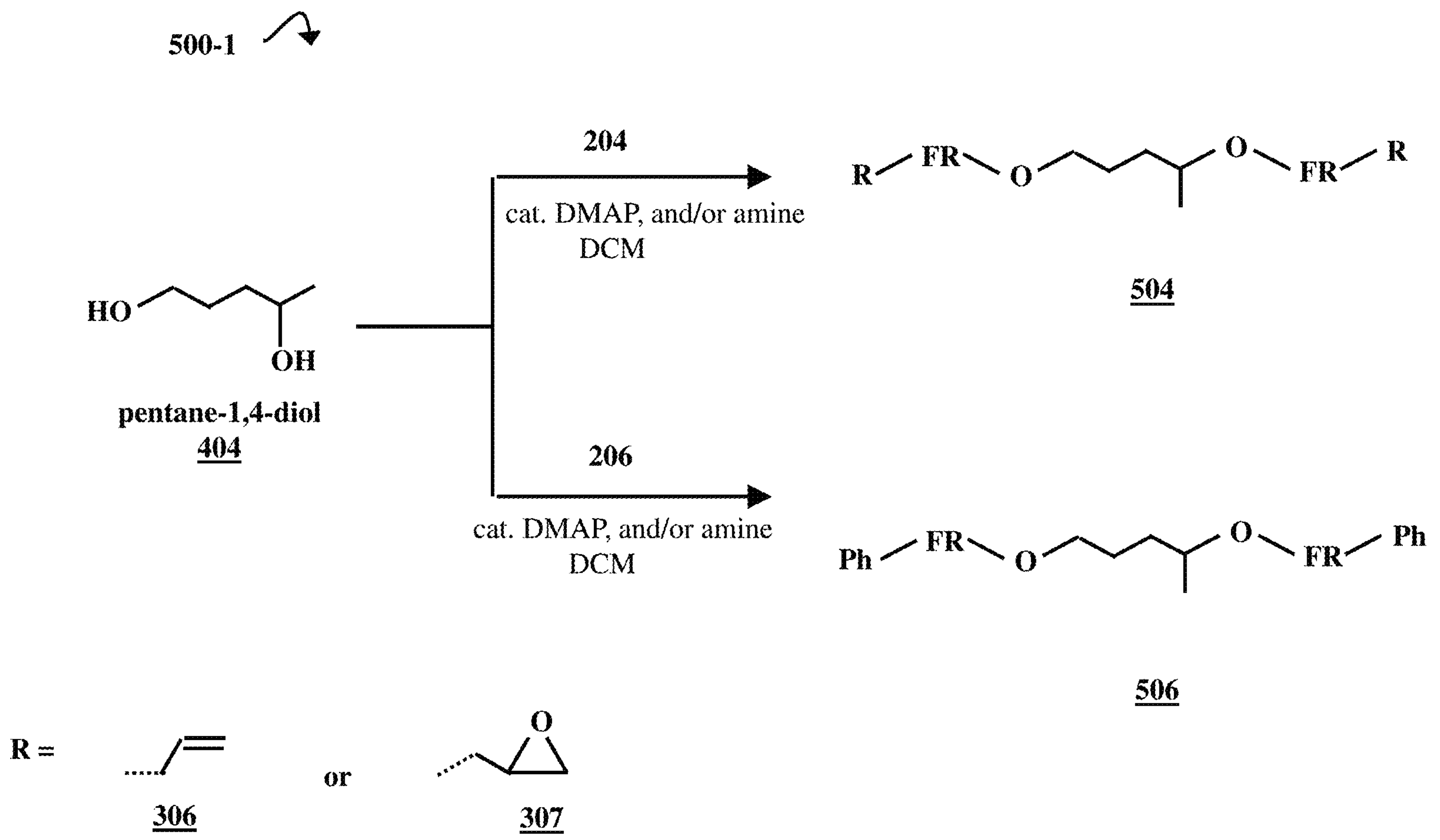

500-1
HO
OH
pentane-1,4-diol
404
204
cat. DMAP, and/or amine
DCM
206
cat. DMAP, and/or amine
DCM
R
FR
O
O
FR
R
504
Ph
FR
O
O
FR
Ph
506
R =
or
O
306
307

FIG. 5A

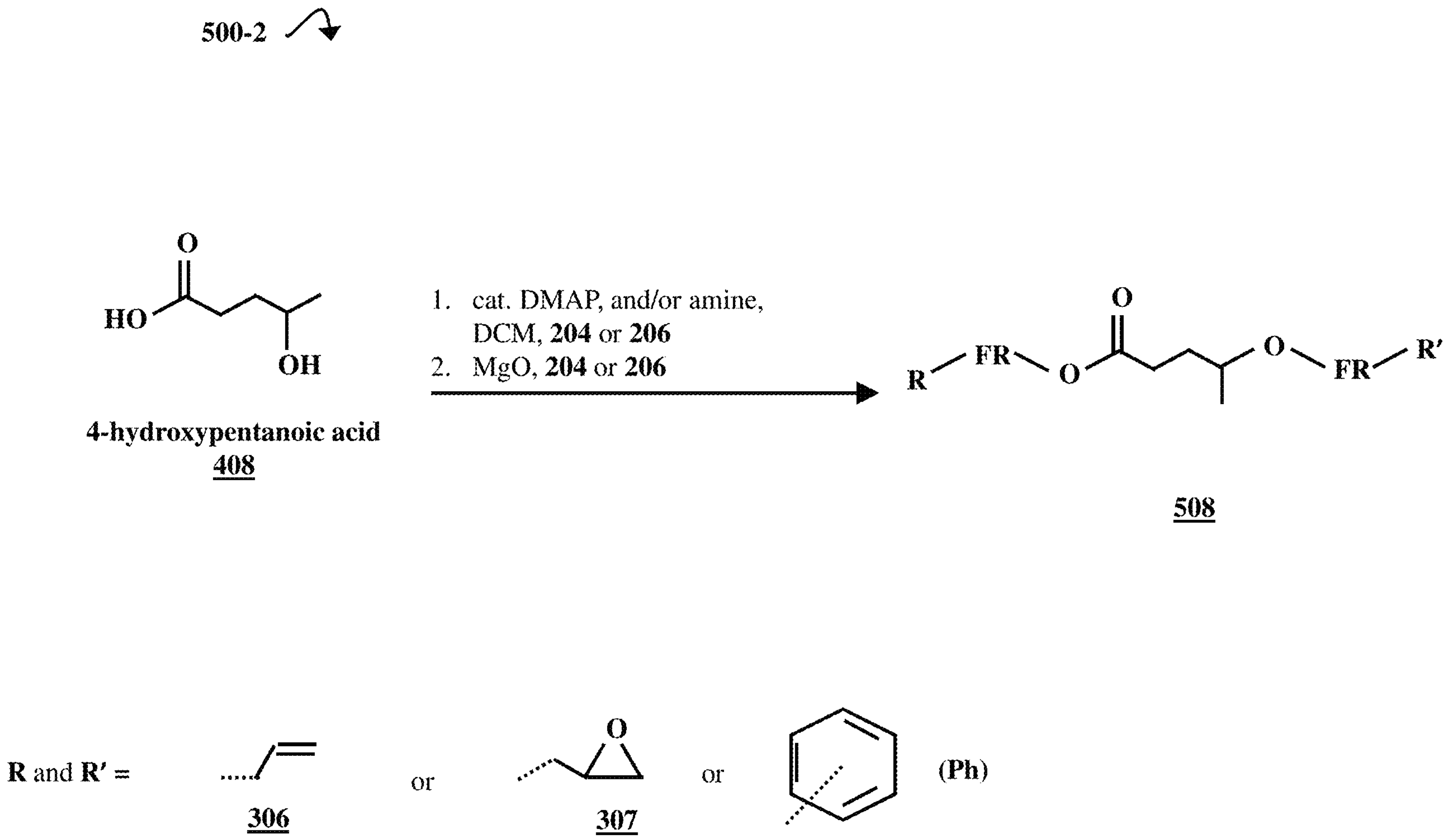

500-2
O
HO
OH
4-hydroxypentanoic acid
408
1. cat. DMAP, and/or amine, DCM, 204 or 206
2. MgO, 204 or 206
O
R
FR
O
O
FR
R′
508
R and R′ =
306
or
O
307
or
(Ph)

FIG. 5B

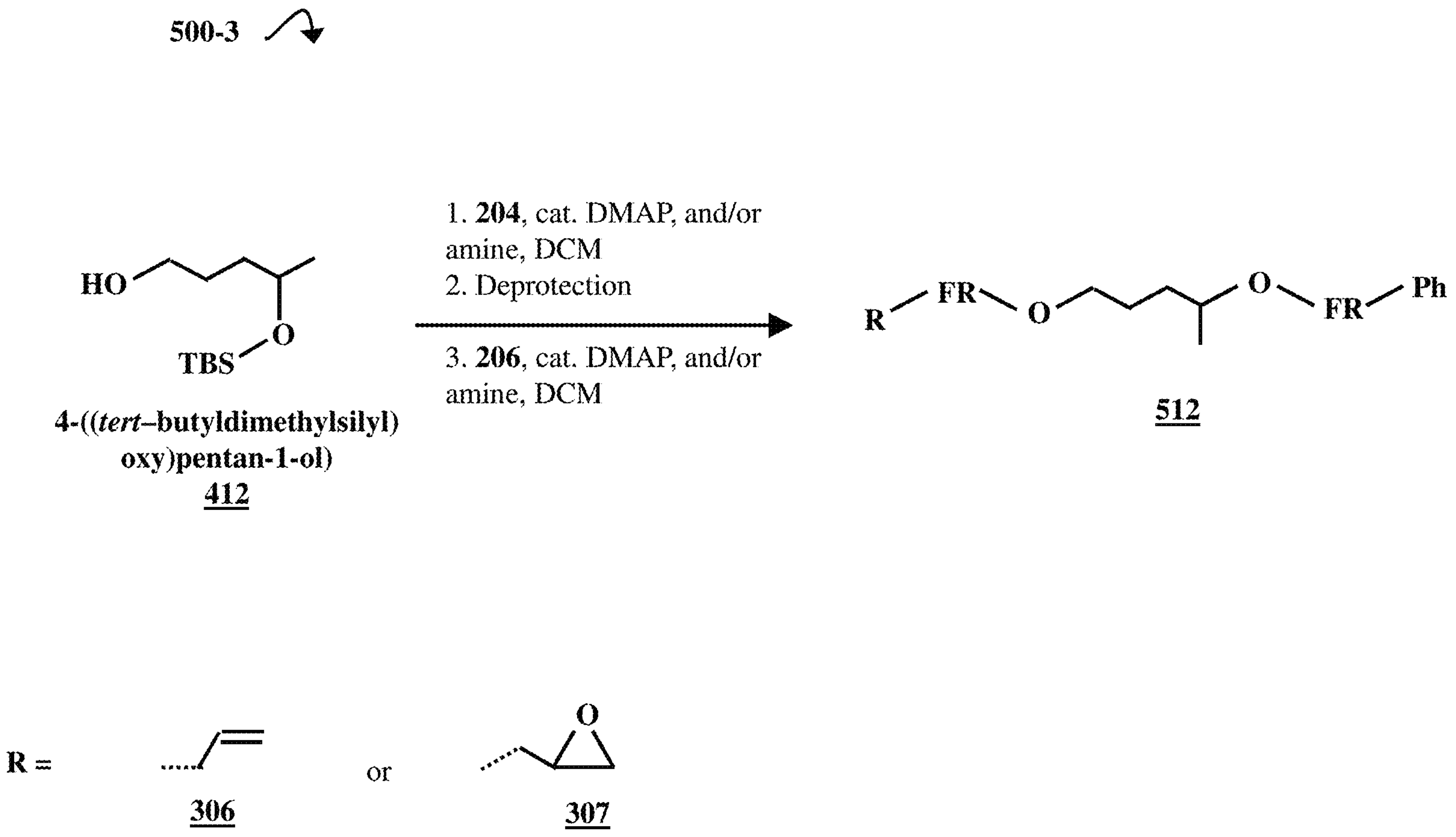

500-3
HO
O
TBS
4-((*tert*–butyldimethylsilyl)
oxy)pentan-1-ol)
412
1. **204**, cat. DMAP, and/or
amine, DCM
2. Deprotection
3. **206**, cat. DMAP, and/or
amine, DCM
R
FR
O
O
FR
Ph
512
R =
306
or
O
307

FIG. 5C

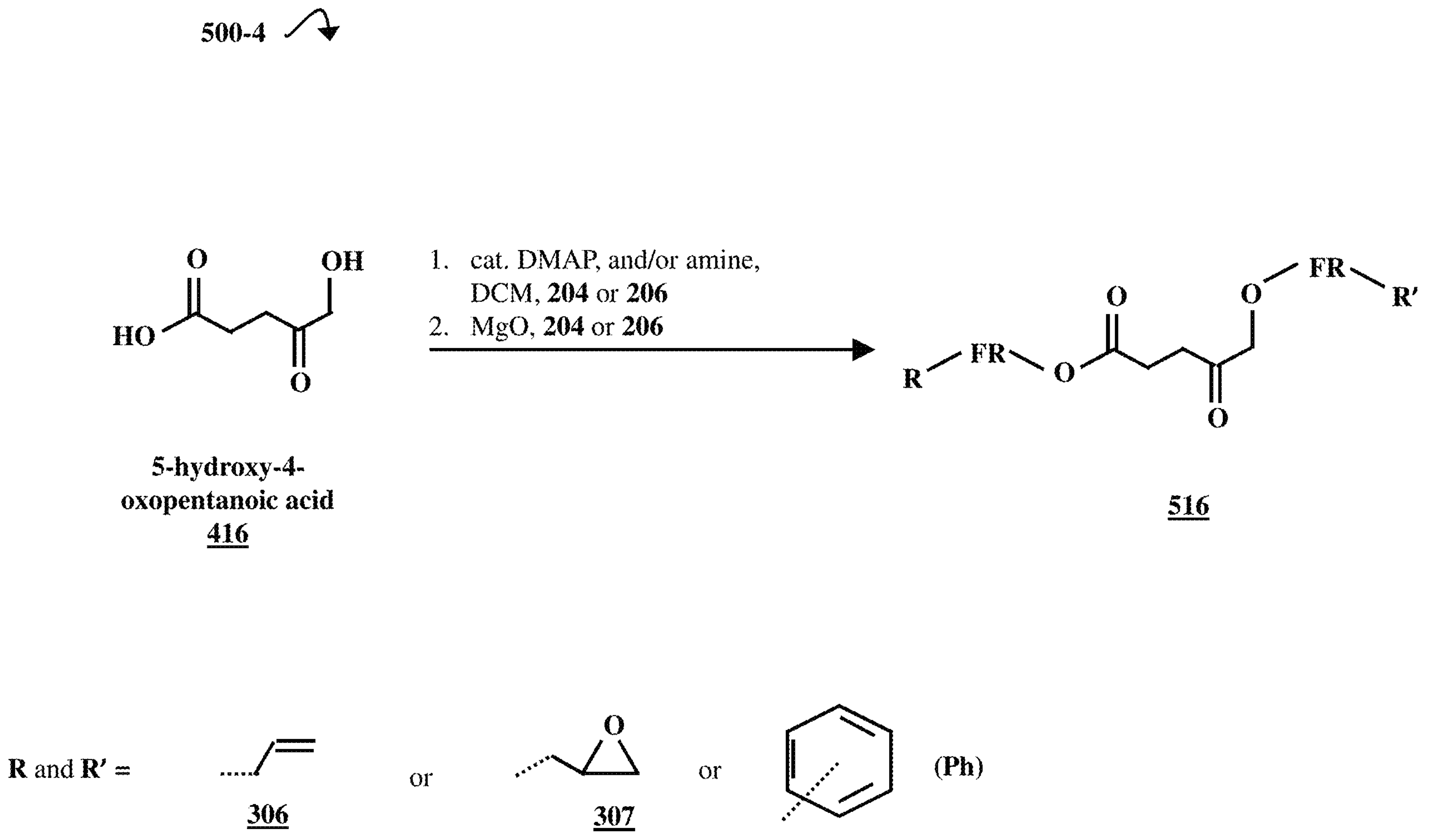

500-4
O
OH
HO
O
5-hydroxy-4-
oxopentanoic acid
416
1. cat. DMAP, and/or amine,
DCM, 204 or 206
2. MgO, 204 or 206
R
FR
O
O
O
O
FR
R'
516
R and R' =
306
or
O
307
or
(Ph)

FIG. 5D

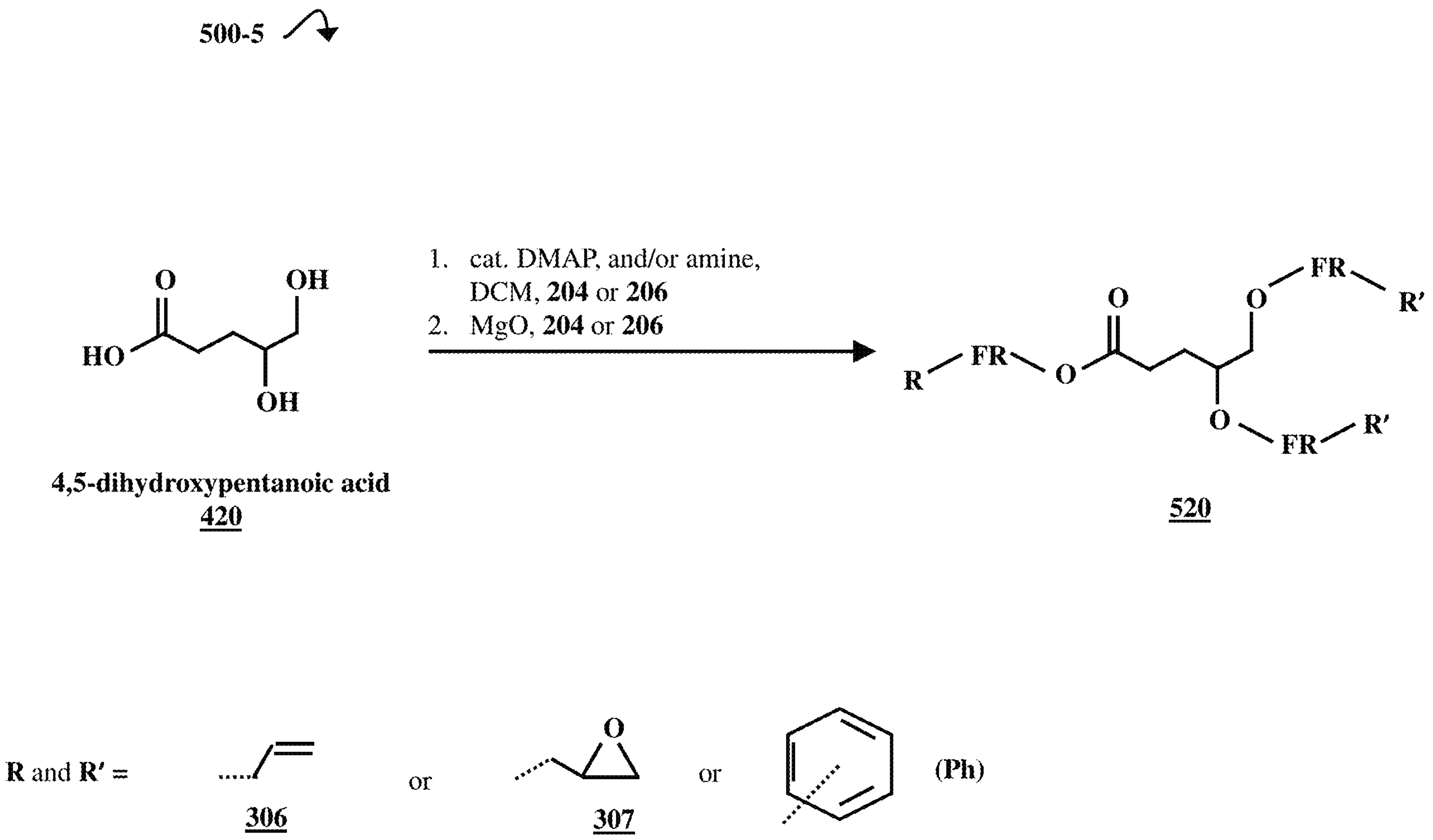

500-5
O
OH
HO
OH
4,5-dihydroxypentanoic acid
420
1. cat. DMAP, and/or amine, DCM, 204 or 206
2. MgO, 204 or 206
O
FR
R'
R
FR
O
O
O
FR
R'
520
R and R' =
306
or
O
307
or
(Ph)

FIG. 5E

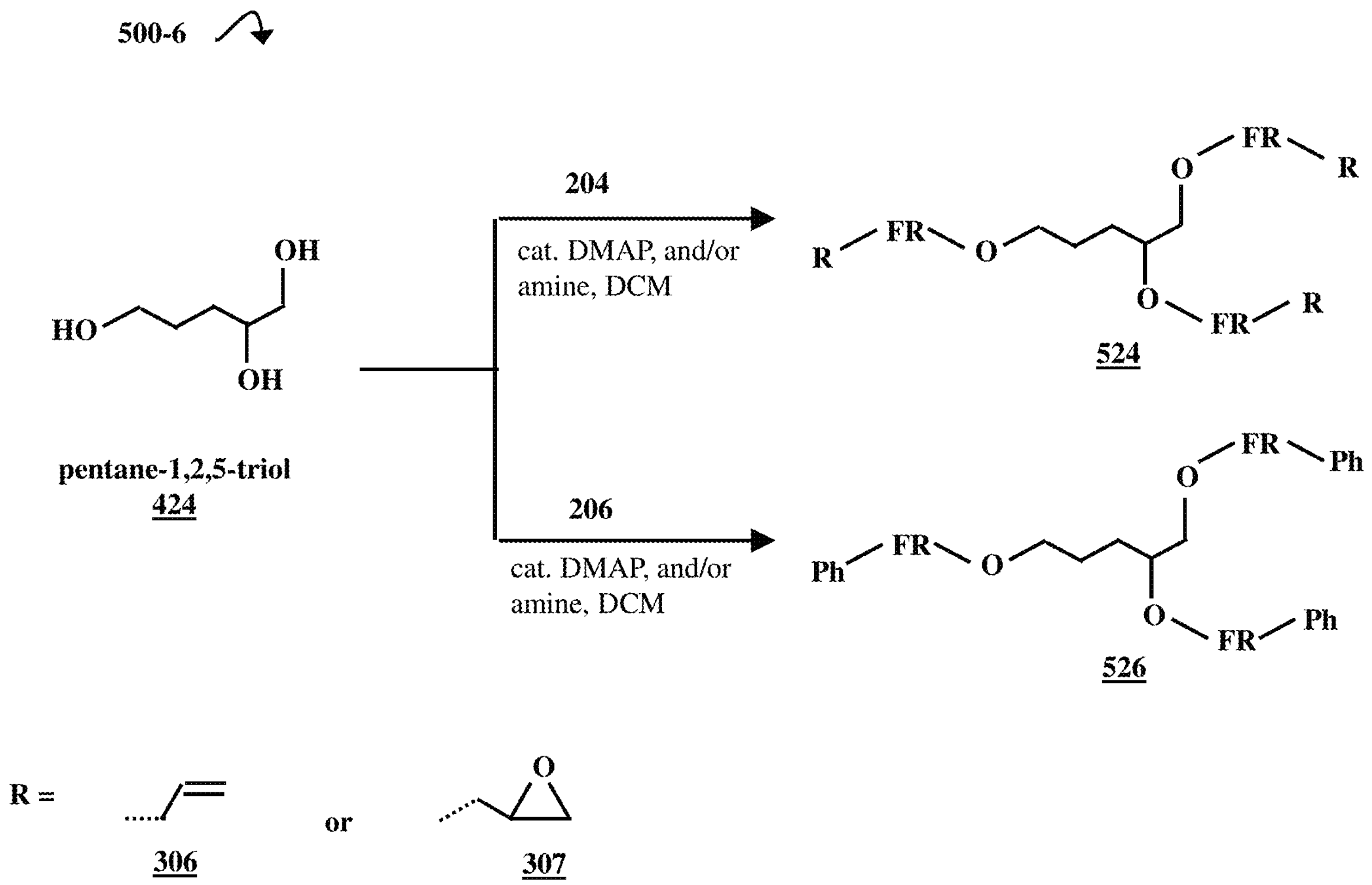

500-6
HO
OH
OH
pentane-1,2,5-triol
424
204
cat. DMAP, and/or amine, DCM
206
cat. DMAP, and/or amine, DCM
R
FR
O
O
FR
R
O
FR
R
524
Ph
FR
O
O
FR
Ph
O
FR
Ph
526
R =
or
306
O
307

FIG. 5F

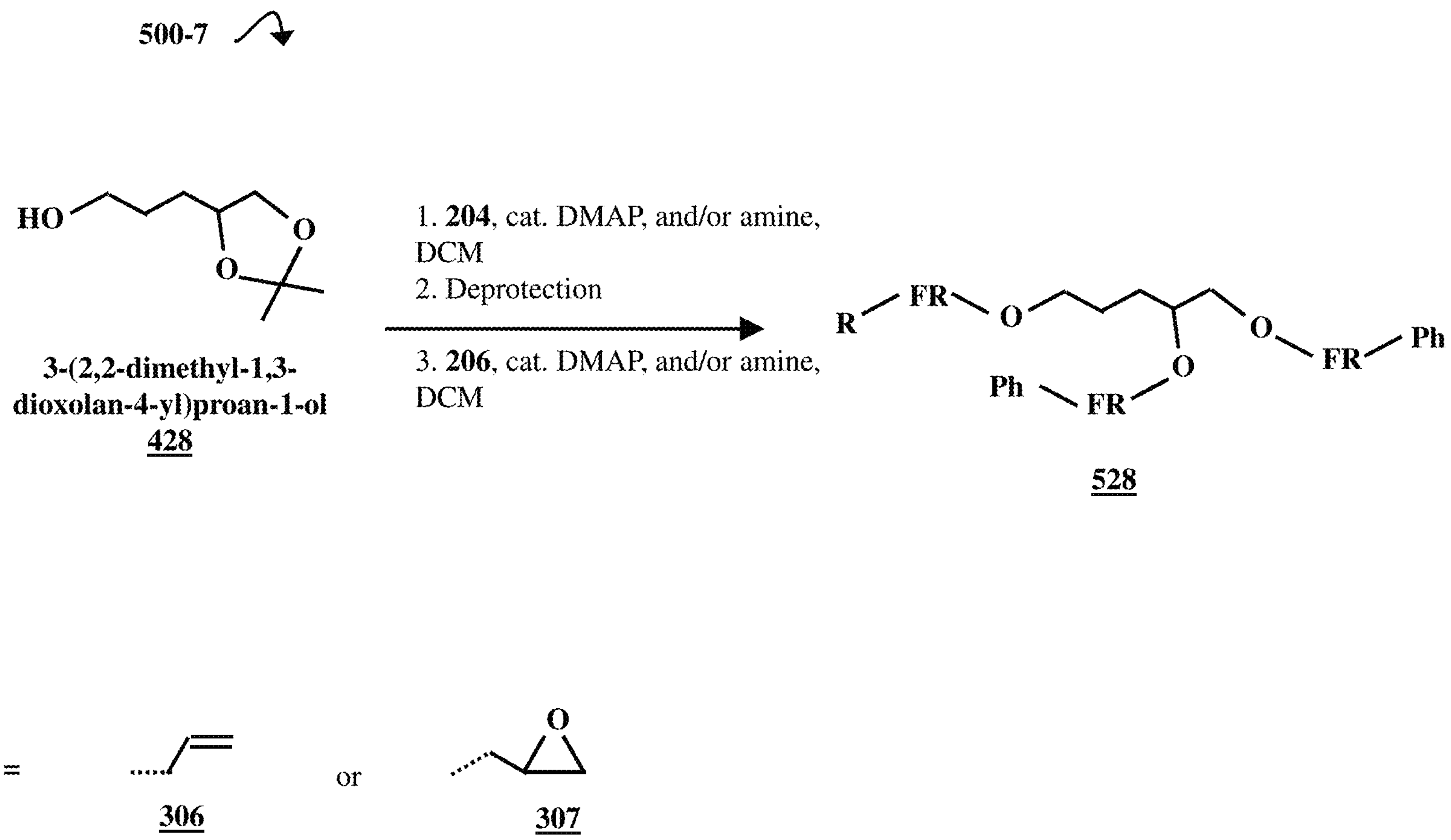

500-7
HO
O
O
3-(2,2-dimethyl-1,3-dioxolan-4-yl)proan-1-ol
428
1. 204, cat. DMAP, and/or amine, DCM
2. Deprotection
3. 206, cat. DMAP, and/or amine, DCM
R
FR
O
O
O
FR
Ph
Ph
FR
528
R =
306
or
O
307

FIG. 5G

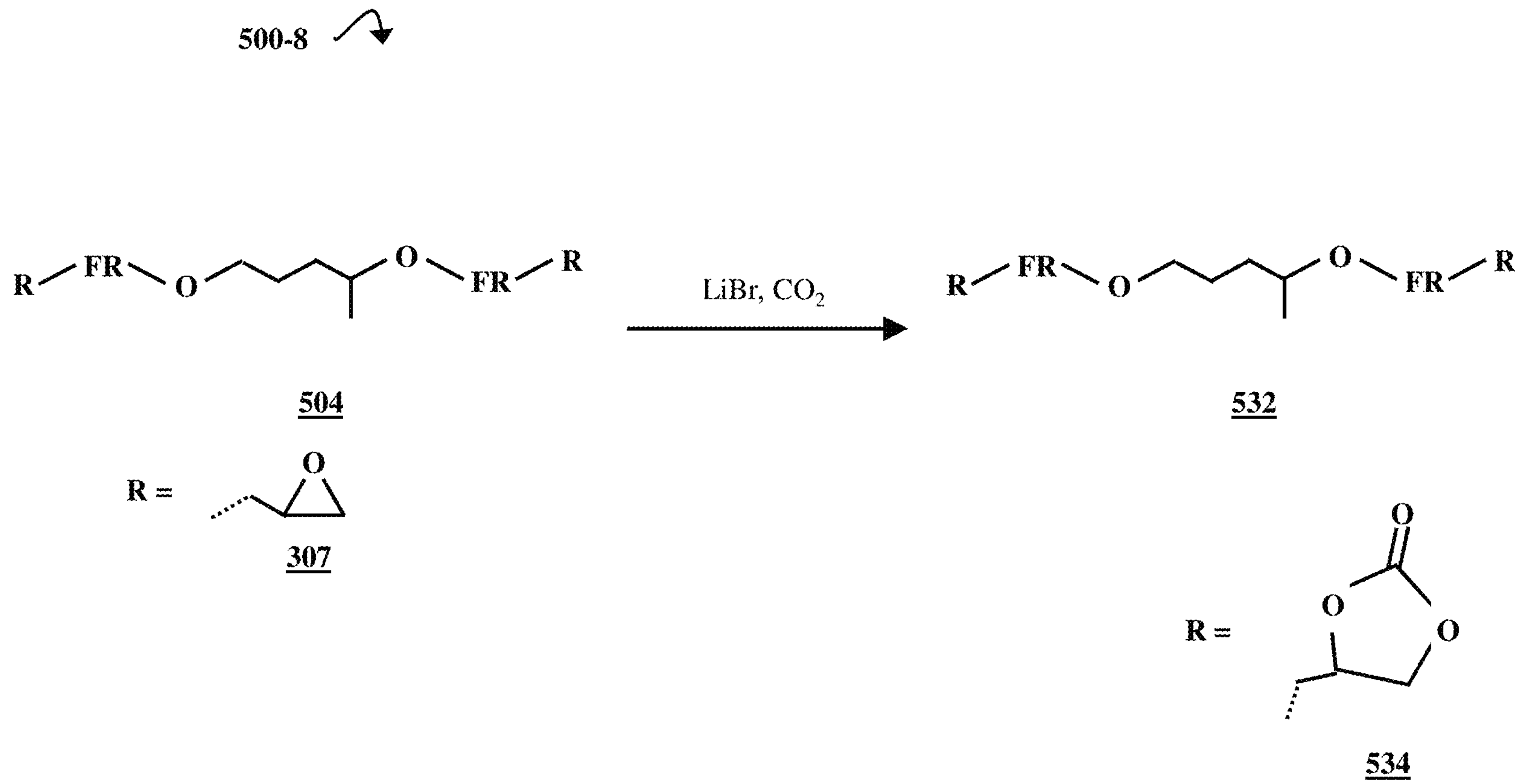
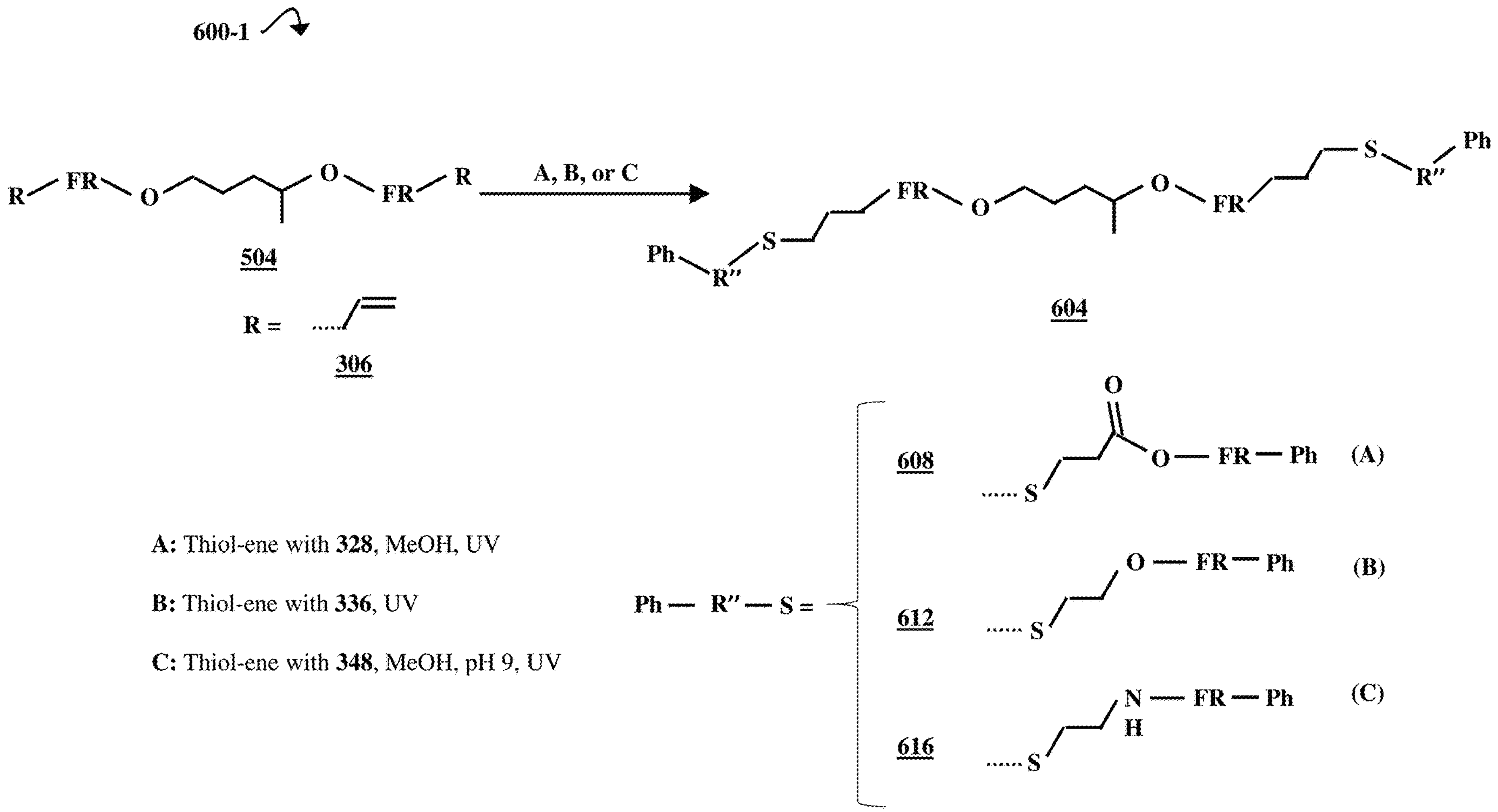


FIG. 5H

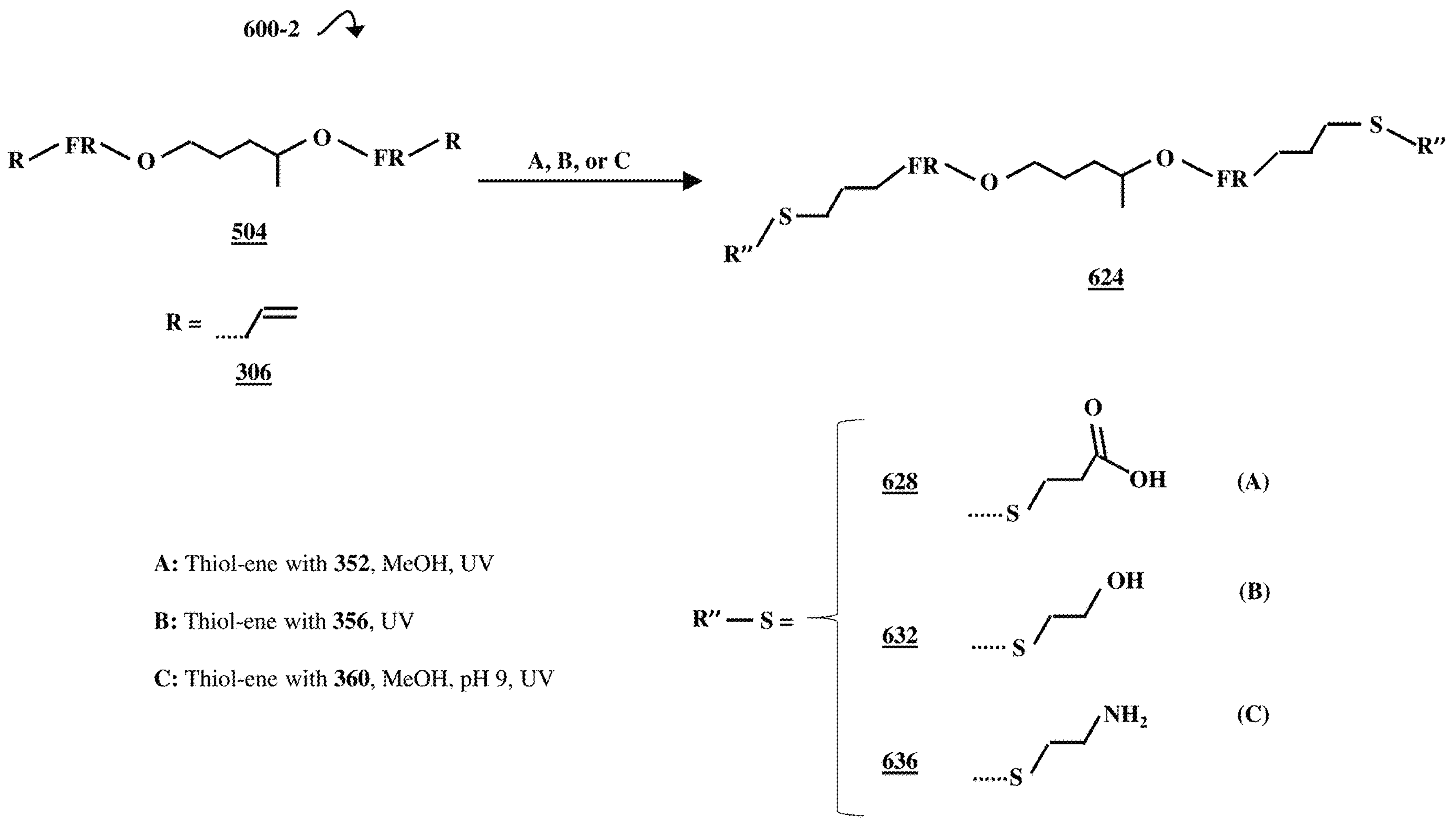


A: Thiol-ene with **328**, MeOH, UV

B: Thiol-ene with **336**, UV

C: Thiol-ene with **348**, MeOH, pH 9, UV

FIG. 6A

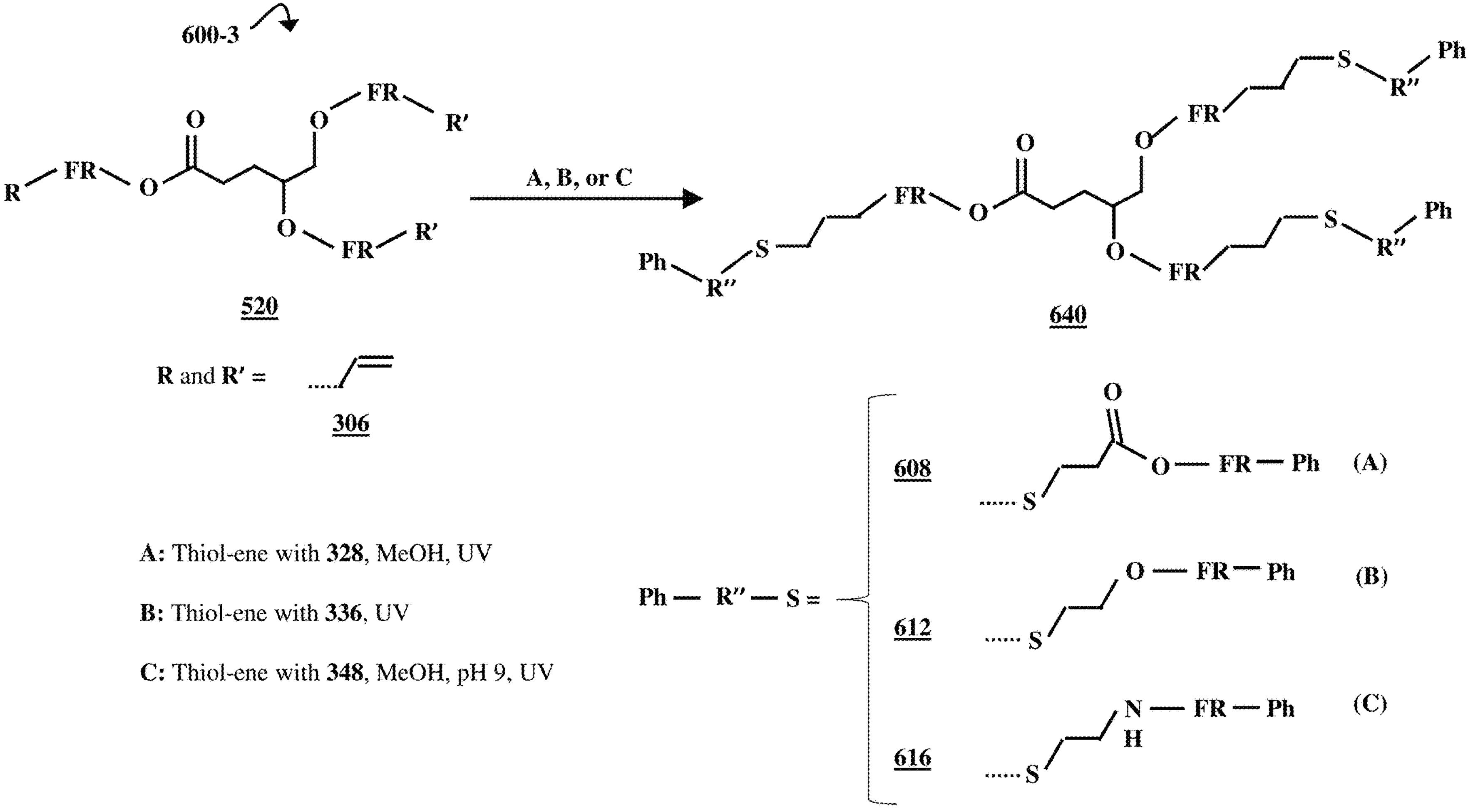


A: Thiol-ene with **352**, MeOH, UV

B: Thiol-ene with **356**, UV

C: Thiol-ene with **360**, MeOH, pH 9, UV

FIG. 6B

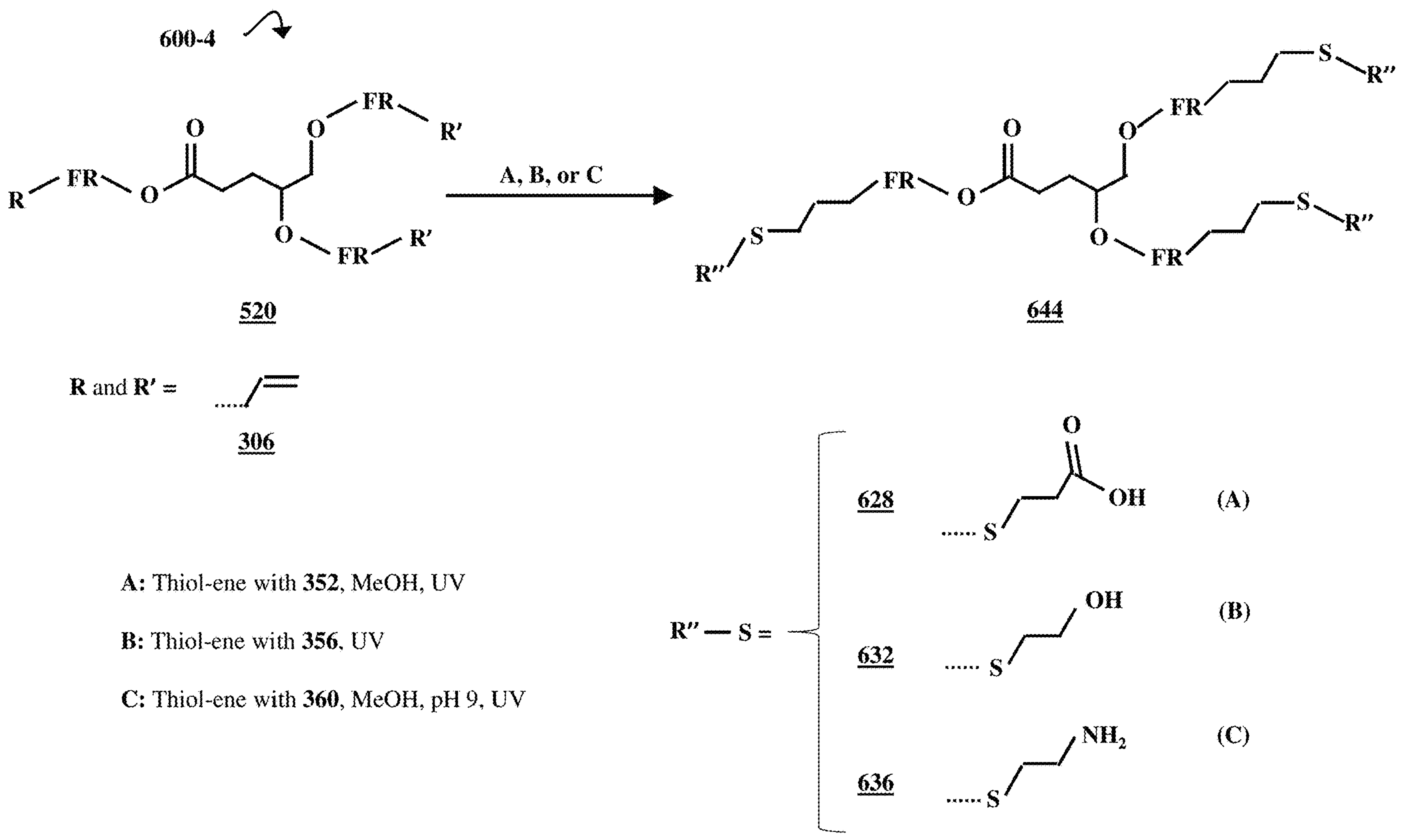


A: Thiol-ene with **328**, MeOH, UV

B: Thiol-ene with **336**, UV

C: Thiol-ene with **348**, MeOH, pH 9, UV

FIG. 6C



A: Thiol-ene with **352**, MeOH, UV

B: Thiol-ene with **356**, UV

C: Thiol-ene with **360**, MeOH, pH 9, UV

FIG. 6D

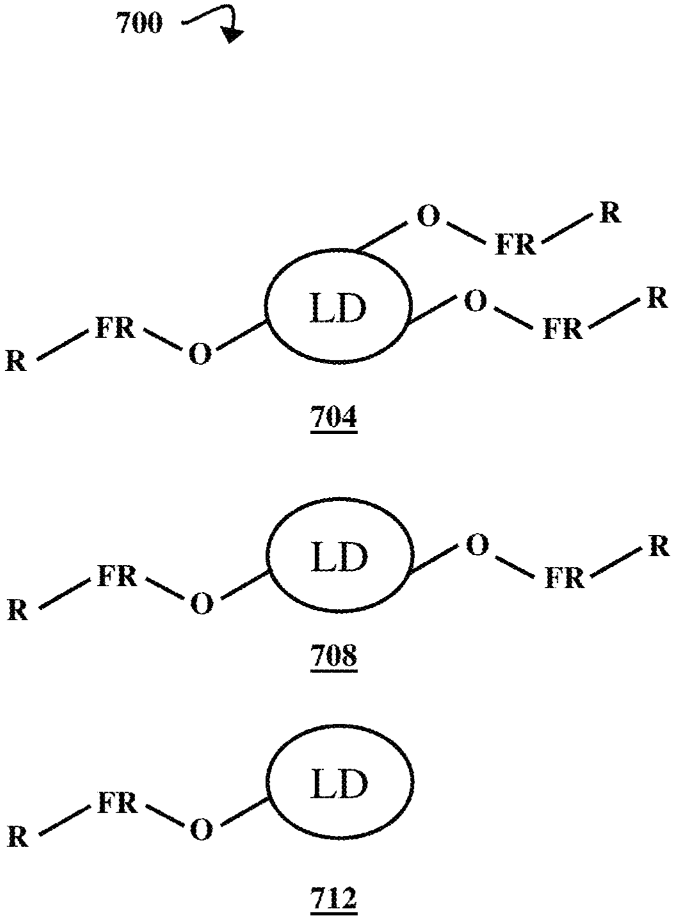


FIG. 7A

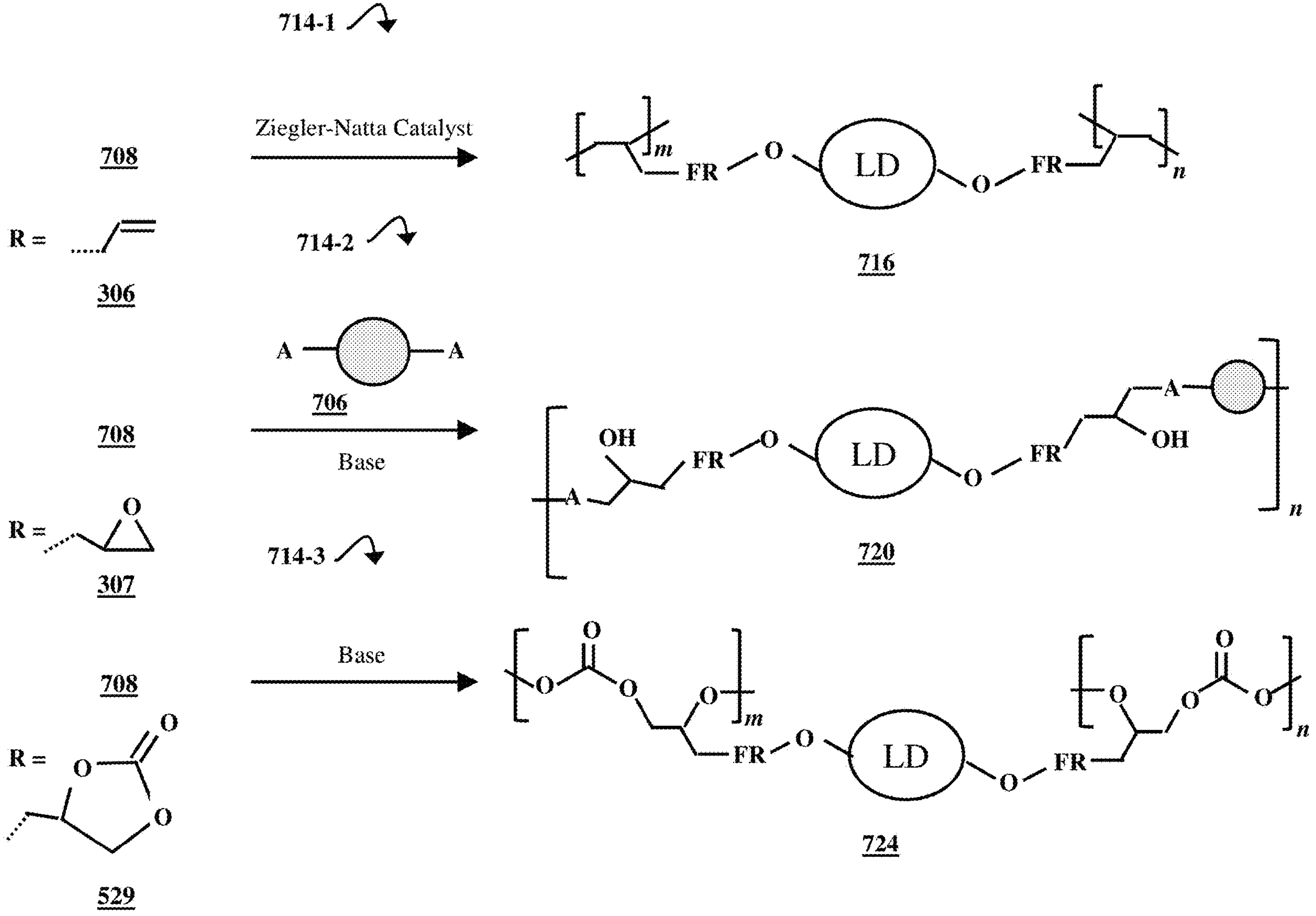

714-1
708
Ziegler-Natta Catalyst
R =
306
m
FR
O
LD
O
FR
n
716
714-2
A
A
706
708
Base
R =
O
307
OH
A
FR
O
LD
O
FR
OH
A
n
720
714-3
Base
708
R =
O
O
O
529
O
O
O
O
m
FR
O
LD
O
FR
O
O
O
O
n
724

FIG. 7B

FLAME RETARDANT LEVULINIC ACID-BASED COMPOUNDS

BACKGROUND

The present disclosure relates to bio-renewable flame retardant compounds and, more specifically, to flame retardant levulinic acid-based compounds.

Bio-based, sustainable compounds can be used in the syntheses of substances that previously required petroleum-based raw materials. Examples of uses for bio-based compounds include polymers, flame retardants, cross-linkers, etc. There are numerous strategies for efficiently and inexpensively producing bio-based compounds on an industrial scale. Examples of these strategies can be found in fermentation technologies, membrane technologies, and genetic engineering. Levulinic acid (4-oxopentanoic acid) is one example of a bio-based compound that can have applications as a component of various polymers, resins, and small molecules. Levulinic acid can be produced by heating hexoses (e.g., glucose, fructose, etc.) or starches in dilute hydrochloric acid or sulfuric acid.

SUMMARY

Various embodiments are directed to flame retardant levulinic acid-based compounds. The flame retardant levulinic acid-based compounds can have variable moieties, which can include a phenyl-substituted flame retardant group, an R-functionalized flame retardant group, a methylene bridge group, a carbonyl group, a methine group with an ether-linked phenyl-substituted flame retardant group, a methine group with an ether-linked R-functionalized flame retardant group, a methyl group, a methylene bridge to an ether-linked phenyl-substituted flame retardant group, and a methylene bridge to an ether-linked R-functionalized flame retardant group. The R-functionalized flame retardant group can have functional groups such as allyl, epoxy, and propylene carbonate. Further, the flame retardant groups can include phosphonyl and/or phosphoryl moieties. The flame retardant levulinic acid-based compound can be incorporated into a polymer to form a flame retardant polymer.

Additional embodiments are directed to a process of forming a flame retardant levulinic acid-based polymer. The flame retardant levulinic acid-based polymer can be produced by forming a phosphorus-based flame retardant molecule, forming a levulinic acid derivative, chemically reacting the phosphorus-based flame retardant molecule and the levulinic acid derivative to form a flame retardant levulinic acid-based compound, and incorporating the levulinic acid-based flame retardant compound into a polymer to form the flame retardant polymer. The levulinic acid derivative can be synthesized from levulinic acid that comes from a bio-based source. The phosphorus-based flame retardant molecule can be a thiol, or a phosphorus-based molecule with allyl, epoxy, or phenyl groups. The flame retardant levulinic acid-based compound can have at least one functional group such as an allyl group, an epoxy group, a propylene carbonate group, a carboxylic acid group, an amine group, or a hydroxyl group. Additionally, the flame retardant levulinic acid-based compound can be incorporated into the polymer by blending, binding, or polymerizing.

Further embodiments are directed to an article of manufacture comprising a material that contains a flame retardant levulinic acid-based polymer. The article of manufacture can also contain an electronic component. Additionally, the material containing the flame retardant levulinic acid-based polymer can be a plastic for integrated circuit packing or an adhesive.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a flow diagram illustrating a process of forming a levulinic acid-based flame retardant polymer, according to some embodiments of the present disclosure.

FIG. **2**A is a diagrammatic representation of the molecular structures of R-functionalized phosphorus-based flame retardant molecules, phenyl-substituted flame retardant phosphorus-based flame retardant molecules, and levulinic acid, according to some embodiments of the present disclosure.

FIG. **2**B is a diagrammatic representation of the molecular structure of a generic levulinic acid-based flame retardant compound.

FIG. **3**A is a chemical reaction diagram illustrating two processes of synthesizing an R-functionalized phosphate-based flame retardant molecule, according to some embodiments of the present disclosure.

FIG. **3**B is a chemical reaction diagram illustrating two processes of synthesizing an R-functionalized phosphonate-based flame retardant molecule, according to some embodiments of the present disclosure.

FIG. **3**C is a chemical reaction diagram illustrating a process of synthesizing a carboxylic acid-derived flame retardant thiol molecule and a process of synthesizing a hydroxy-derived flame retardant thiol molecule, according to some embodiments of the present disclosure.

FIG. **3**D is a chemical reaction diagram illustrating a process of synthesizing an amine-derived flame retardant thiol molecule, according to some embodiments of the present disclosure.

FIG. **3**E is a diagrammatic representation of the molecular structures of three thiol molecules that are involved in the synthesis of levulinic acid-based compounds, according to some embodiments of the present disclosure.

FIG. **4**A is chemical reaction diagram illustrating processes of synthesizing the levulinic acid-derived compounds pentane-1,4-diol, 4-hydroxypentanoic acid, 4-((tert-butyldimethylsilyl)oxy)pentan-1-ol), and 5-hydroxy-4-oxopentanoic acid, according to some embodiments of the present disclosure.

FIG. **4**B is a chemical reaction diagram illustrating processes of synthesizing 5-hydroxy-4-oxopentanoic acid-derived 4,5-dihydroxypentanoic acid, pentane-1,2,5-triol, and 3-(2,2-dimethyl-1,3-dioxolan-4-yl)propan-1-ol, according to some embodiments of the present disclosure.

FIG. **5**A is a chemical reaction diagram illustrating a process of forming a difunctionalized pentane-1,4-diol-based flame retardant compound and a phenyl-substituted pentane-1,4-diol-based flame retardant compound, according to some embodiments of the present disclosure.

FIG. **5**B is a chemical reaction diagram illustrating a process of forming R-functionalized and/or phenyl-substituted 4-hydroxypentanoic acid-derived flame retardant compounds, according to some embodiments of the present disclosure.

FIG. **5**C is a chemical reaction diagram illustrating a process of forming a monofunctionalized 4-((tert-butyldimethylsilyl)oxy)pentan-1-ol-derived flame retardant compound, according to some embodiments of the present disclosure.

FIG. **5**D is a chemical reaction diagram illustrating a process of forming R-functionalized and/or phenyl-substituted 5-hydroxy-4-oxopentanoic acid-derived flame retardant compounds, according to some embodiments of the present disclosure.

FIG. **5**E is a chemical reaction diagram illustrating a process of forming R-functionalized and/or phenyl-substituted 4,5-dihydroxypentanoic acid-derived flame retardant compounds, according to some embodiments of the present disclosure.

FIG. **5**F is a chemical reaction diagram illustrating a process of forming a trifunctionalized pentane-1,2,5-triol-derived flame retardant compound and a phenyl-substituted pentane-1,2,5-triol-derived flame retardant compound, according to some embodiments of the present disclosure.

FIG. **5**G is a chemical reaction diagram illustrating a process of forming a monofunctionalized 3-(2,2-dimethyl-1,3-dioxolan-4-yl)propan-1-ol-derived flame retardant compound, according to some embodiments of the present disclosure.

FIG. **5**H is a chemical reaction diagram illustrating a process of forming a propylene carbonate-functionalized levulinic acid-based flame retardant compound, according to some embodiments of the present disclosure.

FIG. **6**A is a chemical reaction diagram illustrating a process of forming phenyl-substituted thioether-linked flame retardant pentane-1,4-diol-based compounds, according to some embodiments of the present disclosure.

FIG. **6**B is a chemical reaction diagram illustrating a process of forming difunctionalized thioether-linked flame retardant pentane-1,4-diol-based compounds, according to some embodiments of the present disclosure.

FIG. **6**C is a chemical reaction diagram illustrating a process of forming phenyl-substituted thioether-linked flame retardant 4,5-dihydroxypentanoic acid-derived compounds, according to some embodiments of the present disclosure.

FIG. **6**D is a chemical reaction diagram illustrating a process of forming trifunctionalized thioether-linked flame retardant 4,5-dihydroxypentanoic acid-derived compounds, according to some embodiments of the present disclosure.

FIG. **7**A is a diagrammatic representation of the structures of generic R-functionalized levulinic acid-based flame retardant monomers, according to some embodiments of the present disclosure.

FIG. **7**B is a chemical reaction diagram illustrating processes of synthesizing flame retardant levulinic acid-based polymers from flame retardant levulinic acid-based compounds, according to some embodiments of the present disclosure.

DETAILED DESCRIPTION

Bio-based compounds are increasingly being used in the syntheses of substances that previously required petroleum-based raw materials. One benefit of bio-based compounds is that they are from renewable resources. Therefore, these compounds have applications in sustainable, or “green,” materials. Sustainable materials are becoming more and more prevalent, due to the rising costs of fossil fuels, and increasing environmental regulatory controls. Advances in biotechnology have provided numerous strategies for efficiently and inexpensively producing bio-based compounds on an industrial scale. Examples of these strategies can be found in fermentation technologies, membrane technologies, and genetic engineering. Two approaches that use biotechnologies are plant-based and microorganism-based approaches. Plant-based approaches can involve obtaining a material directly from a plant, or growing plant tissues or cells that can produce bio-based compounds from various substrates using their own biosynthetic pathways. Microorganism-based approaches involve using native or genetically modified fungi, yeast, or bacteria to produce a desired compound from a structurally similar substrate.

Examples of uses for bio-based compounds include polymers, flame retardants, cross-linkers, etc. In some examples, bio-based polymers and petroleum-based polymers are blended to form a polymer composite. However, polymers can also be entirely bio-based, or produced from a combination of bio- and petroleum-based monomers. Bio-based compounds can impart flame retardant properties to bio- and petroleum-based polymers. For example, flame retardant molecules or cross-linkers can be incorporated into polymers. Additionally, flame retardant monomers can be polymerized to form flame retardant polymers.

Levulinic acid (4-oxopentanoic acid) is one example of a bio-based compound that can have applications as a component of various polymers, resins, and monomers. Levulinic acid can be produced by heating hexoses (e.g., glucose, fructose, etc.) or starches (e.g., corn starch, etc.) in dilute hydrochloric acid or sulfuric acid. Commercial production of levulinic acid can occur in a continuous manner using lignocellulose as a starting material, which is treated with dilute mineral acid and transferred to a high-pressure reactor where it is heated with steam to allow the formation of levulinic acid. After cooling and filtering off the solid by-products, the levulinic acid that is formed is separated from the mineral acid catalyst by extraction without neutralization of the acid catalyst. This allows the acid catalyst to be recycled, while the levulinic acid can be purified from the acid-free organic solvent. Pure levulinic acid is isolated by evaporation of the extraction solvent and distillation of the levulinic acid.

According to the present disclosure, levulinic acid is used as a precursor for flame retardant compounds. These compounds can include small molecules, cross-linkers, monofunctional molecules, and monomers. The levulinic acid-based flame retardant compounds can be added to polymers, fabrics, resins, or other materials during blending, curing, foaming, extrusion, or other processing techniques. In addition to directly adding the levulinic acid-based flame retardant monomers to the materials during processing, the added levulinic acid-based flame retardant monomers can be contained within microcapsules.

FIG. **1** is a flow diagram illustrating a process **100** of forming a flame retardant polymer containing a levulinic acid-based flame retardant compound, according to some embodiments of the present disclosure. Process **100** begins with the formation of a phosphorus-based flame retardant molecule. This is illustrated at step **104**. The phosphorus-based flame retardant molecule has either a phosphoryl or a phosphonyl moiety (collectively referred to as an FR group) with an attached R functional group or phenyl (Ph) group. The R groups that are attached to the FR groups can vary, as is discussed in greater detail below. The phosphorus-based flame retardant molecules can be phosphate- or phosphonate-based flame retardant molecules. The structures and syntheses of phosphorus-based flame retardant molecules are discussed in greater detail with respect to FIGS. **3**A-**3**D.

Process **100** continues with the formation of a levulinic acid derivative. This is illustrated at step **108**. The derivatives can have one, two, or three hydroxyl groups to which phosphorus-based flame retardant molecules with allyl or epoxy functional groups can be bound. Examples of levulinic acid derivatives are discussed in greater detail with respect to FIGS. **4**A-**4**B. It should be noted that the formation of the levulinic derivative in step **108** is illustrated as occurring after the formation of the phosphorus-based flame retardant molecule in step **104**. However, in some embodiments, step **108** can occur before step **104**. In some embodiments, steps **104** and **108** can occur simultaneously or can occur at overlapping times.

The levulinic acid derivative and the phosphorus-based flame retardant molecule are chemically reacted in order to form a levulinic acid-based flame retardant compound. This is illustrated at step **112**. The identity of the levulinic acid-based flame retardant compound is determined by the levulinic acid derivative and the phosphorus-based flame retardant molecule used in the reaction. The FR groups are bonded to hydroxyl and/or carboxylic acid groups on the levulinic acid derivatives in a reaction with levulinic acid derivatives and the phosphorus-based flame retardant compounds. The syntheses and structures of levulinic acid-based flame retardant compounds are discussed in greater detail with respect to FIGS. **5**A-**5**H and FIGS. **6**A-**6**D.

The levulinic acid-based flame retardant compound formed in step **112** is polymerized, or added to another polymer, yielding a flame retardant levulinic acid-based polymer. This is illustrated at step **116**. The levulinic acid-based flame retardant compounds can be added to a polymer as small molecules, cross-linkers, or bound monofunctional molecules. Further, the flame retardant levulinic acid-based compound can be polymerized in a reaction with a base and/or a second monomer. Additionally, in some embodiments, the flame retardant levulinic acid-based compound can be polymerized in a reaction with a Ziegler-Natta catalyst. Polymerization reactions with the flame retardant levulinic acid-based compounds are discussed in greater detail with respect to FIG. **7**B.

FIG. **2**A is a diagrammatic representation **200-1** of the molecular structures of R-functionalized phosphorus-based flame retardant molecules **204-1** and **204-2** (referred to herein collectively as **204**), phenyl-substituted phosphorus-based flame retardant molecules **206-1** and **206-2** (referred to collectively as **206**), and levulinic acid **208**, according to some embodiments of the present disclosure. Each phosphorus-based flame retardant molecule is either a phosphate-based flame retardant molecule **204-1** and **206-1** or phosphonate-based flame retardant molecule **204-2** and **206-2**. Herein, phosphoryl and phosphonyl moieties in the phosphate- and phosphonate-based molecules, respectively, are replaced by the abbreviation "FR" in order to simplify illustrations of the molecular structures. The moieties replaced by the abbreviation each have a phenyl substituent. However, this phenyl can be replaced by another alkyl substituent (e.g., methyl, ethyl, propyl, and isopropyl, etc.).

The compounds referred to as phenyl-substituted flame retardant phosphorus-based flame retardant molecules **206**, each have two phenyl (Ph) substituents. The compounds referred to as R-functionalized phosphorus-based flame retardant molecules **204** each have an R functional group in addition to a single phenyl (Ph) substituent. In some embodiments, the phenyl substituents are replaced by another alkyl substituent (e.g., methyl, ethyl, propyl, and isopropyl, etc.). Example syntheses of the R-functionalized phosphorus-based flame retardant molecules **204** are discussed with respect to FIGS. **3**A and **3**B. The phosphorus-based flame retardant molecules **204** and **206** are reacted with levulinic acid derivatives to form levulinic acid-based flame retardant compounds.

Herein, levulinic acid-based flame retardant compounds are referred to as R-functionalized (monofunctionalized, difunctionalized, or trifunctionalized) or phenyl-substituted. The terminal R groups attached to FR moieties (e.g., allyl, epoxy, and propylene carbonate) are involved in binding to polymer chains or in polymerization reactions, while the phenyl substituents on the FR moieties do not participate in these reactions. Therefore, any compound with at least one R functional group is referred to as R-functionalized to indicate that it can participate in binding or polymerization. Levulinic acid-based flame retardant compounds with only phenyl-substituents on their FR moieties cause a polymer to be flame retardant when blended into the polymer.

FIG. **2**B is a diagrammatic representation **200-2** of the molecular structure of a generic levulinic acid-based flame retardant compound **212**, according to some embodiments of the present disclosure. The levulinic acid-based flame retardant compound **212** has several variable positions, which are represented by "M" in the diagram. These positions can have functional groups (e.g., R groups) that will participate in polymerization reactions, or bind to polymers. The positions can also have substituents (e.g., phenyl (Ph) or other alkyl groups) that do not participate in binding or polymerization. When the levulinic acid-based flame retardant compound **212** has a single functional group, it can bind to polymer chains, or be polymerized. Further, when the levulinic acid-based flame retardant compound **212** has more than one functional group, it can bind to polymer chains, act as a cross-linker, or be polymerized. When the levulinic acid-based flame retardant compound **212** has no R groups to participate in binding or polymerization, it can be blended with a polymer as a flame retardant small molecule. These properties are discussed in greater detail below.

Additionally, examples of M moieties are illustrated in FIG. **2**B. For example, M^1 is a flame retardant group **216-1** with an R-group functionalization (**216-7**), a phenyl-substituent (**216-8**), a thioether-linked phenyl-substituted flame retardant group (**216-9**), or a thioether-linked R-substituted flame retardant group (**216-10**); M^2 is either carbonyl group **216-2** or methylene bridge 216-3; M^3 is either carbonyl group **216-3** or a methine group with an ether-linked flame retardant group **216-5** with an R-group functionalization (**216-7**), a phenyl-substituent (**216-8**), a thioether-linked phenyl-substituted flame retardant group (**216-9**), or a thioether-linked R-substituted flame retardant group (**216-10**); and M^4 is either a methyl group **216-4**, a methylene bridge to an ether-linked flame retardant group **216-5** with an R-group functionalization (**216-7**), a phenyl-substituent (**216-8**), a thioether-linked phenyl-substituted flame retardant group (**216-9**), or a thioether-linked R-substituted flame retardant group (**216-10**). While thioether-linked phenyl-substituted flame retardant group (**216-9**) and thioether-linked R-substituted flame retardant group (**216-10**) are depicted with three-carbon chains, chains of varying lengths (e.g., three to fourteen carbons, etc.) could be used. Specific examples of R functional groups and levulinic acid-based flame retardant compounds are discussed in greater detail below.

FIG. **3**A is a chemical reaction diagram illustrating two processes **300-1** and **300-2** of synthesizing an R-functionalized phosphate-based flame retardant molecule **204-1**, according to some embodiments of the present disclosure. In both processes **300-1** and **300-2**, an alcohol **304** is a starting material for the R-functionalized phosphate-based flame retardant molecule **204-1**. The alcohol **304** has either an allyl R group **306** or an epoxy R group **307**. It should be noted that, though an allyl group **306** with a single methylene spacer group is illustrated here, other alcohols with allylic chains of varying lengths (e.g., one to twelve methylene spacer groups, etc.) could be used. Additionally, alcohols with acrylate substituents are used in some embodiments.

In process **300-1**, the alcohol **304** is reacted with diphenyl phosphonate and titanium isopropoxide ($Ti(O^iPr)_4$) in benzene to produce a precursor **308** to the R-functionalized phosphate-based flame retardant molecule **204-1**. In this pseudo-transesterification reaction, the precursor **308** is formed when a phenyl (Ph) substituent on diphenyl phosphonate is replaced by the R group from the alcohol **304**. The precursor **308** is then reacted with thionyl chloride ($SOCl_2$) and carbon tetrachloride (CCl_4) over a range of approximately 0° C. to approximately room temperature (RT, e.g., 15-25° C.), forming the R-functionalized phosphate-based flame retardant molecule **204-1**. In process **300-2**, the alcohol **304** is reacted with phenyl dichlorophosphate in a tetrahydrofuran (THF) solution containing triethyl amine (Et_3N). This process is carried out over a range of approximately 0° C. to approximately room temperature (RT, e.g., 15-25° C.). A chloride on the phenyl dichlorophosphate is replaced by the alcohol **304**, forming the R-functionalized phosphate-based flame retardant molecule **204-1**.

FIG. **3**B is a chemical reaction diagram illustrating two processes **300-3** and **300-4** of synthesizing an R-functionalized phosphonate-based flame retardant molecule **204-2**, according to some embodiments of the present disclosure. In both processes **300-3** and **300-4**, an organochloride **312** is a starting material for the R-functionalized phosphonate-based flame retardant molecule **204-2**. The organochloride **312** has either an allyl R group **306** or an epoxy R group **307**. It should be noted that, as in the case of the alcohol **304**, other organochlorides with allylic chains of varying lengths (e.g., one to twelve methylene spacer groups, etc.) could be used. Additionally, organochlorides with acrylate substituents are used in some embodiments.

In process **300-3**, the organochloride **312** is reacted with triphenyl phosphite ($P(OPh)_3$). The mixture is heated, either by refluxing in toluene or microwaving (mw) in ethanol (EtOH), producing a phosphonyl ester precursor **316** to the R-functionalized phosphonate-based flame retardant molecule **204-2**. The phosphonyl ester precursor **316** is reacted with phosphorus pentachloride (PCl_5) to form the R-functionalized phosphonate-based flame retardant molecule **204-2**.

In process **300-4**, a mixture of the organochloride **312** and triphenyl phosphite ($P(OPh)_3$) is heated, either by refluxing in toluene or microwaving (mw) in ethanol (EtOH), forming a phenylphosphinic acid precursor **320** to the R-functionalized phosphonate-based flame retardant molecule **204-2**. The reaction is then quenched by raising the pH of the solution. In this prophetic example, an ethanol (EtOH)/water (H_2O) solution of sodium hydroxide (NaOH) is added to the reaction mixture. However, in some embodiments, bases other than sodium hydroxide, such as potassium hydroxide or lithium hydroxide, are used to quench the reaction. When the reaction has been quenched, thionyl chloride ($SOCl_2$) is added to the phenylphosphinic acid precursor **320**, producing the R-functionalized phosphonate-based flame retardant molecule **204-2**.

FIG. **3**C is a chemical reaction diagram illustrating a process **300-5** of synthesizing a carboxylic acid-derived flame retardant thiol molecule **328** and a process **300-6** of synthesizing a hydroxy-derived flame retardant thiol molecule **336**, according to some embodiments of the present disclosure. In process **300-5**, acetate-protected thiopropionic acid **324** is reacted with magnesium oxide (MgO) and a phenyl-substituted phosphorus-based flame retardant compound **206** (either diphenyl chlorophosphate (DPCPa) **206-1** or diphenylphosphinic chloride (DPCPo) **206-2**). The acetate group is then removed by refluxing the mixture in an ethanol (EtOH) solution containing sodium hydroxide (NaOH), yielding the carboxylic acid-derived flame retardant thiol molecule **328**. If the process is carried out with DPCPa **206-1**, the carboxylic acid-derived flame retardant thiol molecule **328** will have phosphoryl FR groups, and, if the reaction is carried out with DPCPo **206-2**, the carboxylic acid-derived flame retardant thiol molecule **328** will have phosphonyl FR groups.

In process **300-6**, the alcohol **304** with the allyl R group **306** is reacted with thioacetic acid in a thiol-ene reaction. In the first step of the reaction, oxygen (**02**) is added to a dichloromethane (DCM) solution of the allyl alcohol **304** and thioacetic acid. The mixture is refluxed, resulting in an acetate-protected mercaptopropanol **332**. The second step in the reaction is a substitution reaction involving a phenyl-substituted phosphorus-based flame retardant compound **206** and catalytic dimethylaminopyridine (cat. DMAP), and/or a stoichiometric amount of an organic amine, such as triethylamine (NEt_3). The acetate group is removed by refluxing the mixture in an ethanol (EtOH) solution containing sodium hydroxide (NaOH). This step results in the production of the hydroxy-derived flame retardant thiol molecule **336**. If the process is carried out with DPCPa **206-1**, the hydroxy-derived flame retardant thiol molecule **336** will have phosphoryl FR groups, and, if the reaction is carried out with DPCPo **206-2**, the hydroxy-derived flame retardant thiol molecule **336** will have phosphonyl FR groups.

FIG. **3**D is a chemical reaction diagram illustrating a process **300-7** of synthesizing an amine-derived flame retardant thiol molecule **348**, according to some embodiments of the present disclosure. In process **300-7**, 1-(boc-amino)-3-butene **340** is first reacted with thioacetic acid in a thiol-ene reaction. Azobisisobutyronitrile (AIBN) is added to the dioxane solution of 1-(boc-amino)-3-butene **340** and thioacetic acid, and the mixture is stirred at approximately 75° C., resulting in an acetate-protected precursor **344** to the amine-derived flame retardant thiol molecule **348**. The second step in process **300-7** is a substitution reaction with a phenyl-substituted phosphorus-based flame retardant compound **206** and catalytic dimethylaminopyridine (cat. DMAP), and/or a stoichiometric amount of an organic amine, such as triethylamine (NEt_3). The acetate group and boc groups are removed under basic conditions (e.g., by refluxing the mixture in an ethanol (EtOH) solution containing sodium hydroxide (NaOH)). This step results in the production of the amine-derived flame retardant thiol molecule **348**. If the process is carried out with DPCPa **206-1**, the amine-derived flame retardant thiol molecule **348** will have phosphoryl FR groups, and, if the reaction is carried out with DPCPo **206-2**, the amine-derived flame retardant thiol molecule **348** will have phosphonyl FR groups.

FIG. **3**E is a diagrammatic representation of the molecular structures **302** of three thiol molecules that are involved in the synthesis of the levulinic acid-based compounds, according to some embodiments of the present disclosure. The three thiol molecules are 3-mercaptopropionate **352**, 2-mercaptoethanol **356**, and cysteamine hydrochloride (HCl) **360**. Each of these thiols can provide a thioether with an R functional group in the synthesis of a functionalized thioether-linked flame retardant levulinic acid-based compound. The syntheses and structures of the functionalized thioether-linked flame retardant levulinic acid-derived compounds are discussed in greater detail with respect to FIGS. **6**B and **6**D.

FIG. **4**A is chemical reaction diagram illustrating processes **400-1**, **400-2**, **400-3**, and **400-4** of synthesizing the levulinic acid-derived compounds pentane-1,4-diol **404**, 4-hydroxypentanoic acid **408**, 4-((tert-butyldimethylsilyl) oxy)pentan-1-ol) **412**, and 5-hydroxy-4-oxopentanoic acid **416**, according to some embodiments of the present disclosure. In process **400-1**, levulinic acid **208** is reduced by lithium aluminum hydride ($LiAlH_4$) in ether. This reduction reaction produces the pentane-1,4-diol **404**. In process **400-2**, levulinic acid **208** is reacted with sodium borohydride ($NaBH_4$) in ether. This reaction produces 4-hydroxypentanoic acid **408**. In process **400-3**, 4-hydroxypentanoic acid **408** is protected with a tert-butyldimethylsilyl (TBS) group, and its carboxylic acid group reduced to give 4-((tert-butyldimethylsilyl)oxy)pentan-1-ol **412**. To do so, **408** 4-hydroxypentanoic acid is reacted with tert-butyldimethylsilyl chloride (TBSCl) and imidazole in DCM. Then the resulting product is reduced by lithium aluminum hydride ($LiAlH_4$) in ether to give 4-((tert-butyldimethylsilyl)oxy)pentan-1-ol **412**. In process **400-4**, levulinic acid **208** is reacted with molecular bromine (Bra) in methanol (MeOH). This process is carried out over a temperature range of approximately 30° C. to approximately 40° C. The product from the first step is refluxed in water in the second step in the reaction. This step produces 5-hydroxy-4-oxopentanoic acid **416**.

FIG. **4**B is a chemical reaction diagram illustrating processes **400-5**, **400-6**, and **400-7** of synthesizing 5-hydroxy-4-oxopentanoic acid-derived 4,5-dihydroxypentanoic acid **420**, pentane-1,2,5-triol **424**, and 3-(2,2-dimethyl-1,3-dioxolan-4-yl)propan-1-ol **428**, according to some embodiments of the present disclosure. In process **400-5**, 5-hydroxy-4-oxopentanoic acid **416** is reacted with $NaBH_4$ in ether. This reaction produces 4,5-dihydroxypentanoic acid **420**. In process **400-6**, 5-hydroxy-4-oxopentanoic acid **416** is reduced by $LiAlH_4$ in ether. This reduction reaction produces pentane-1,2,5-triol **424**. In process **400-7**, pentane-1,2,5-triol **424** is reacted with 2,2-dimethoxypropane **426** and p-toluenesulfonic acid to produce 3-(2,2-dimethyl-1,3-dioxolan-4-yl)propan-1-ol **428**.

FIG. **5**A is a chemical reaction diagram illustrating a process **500-1** of forming a difunctionalized pentane-1,4-diol-based flame retardant compound **504** and a phenyl-substituted pentane-1,4-diol-based flame retardant compound **506**, according to some embodiments of the present disclosure. In both reactions, pentane-1,4-diol **404** is reacted with a phosphorus-based flame-retardant molecule **204** or **206** and catalytic dimethylaminopyridine (cat. DMAP) in a dichloromethane (DCM) solution. When the reaction is carried out with an R-functionalized phosphorus-based compound **204**, allyl-**306** or epoxy-**307** functionalized FR moieties are attached at the hydroxyl groups on pentane-1,4-diol **404**. This reaction forms a difunctionalized pentane-1,4-diol-based flame retardant compound **504**. This compound **504** is a flame retardant levulinic acid-based compound that can be polymerized, or act as a cross-linker in another polymer. Its inclusion in a polymer, either by polymerization or cross-linking, causes the polymer to be flame retardant.

If the reaction **500-1** is carried out with a phenyl-substituted phosphorus based compound **206**, phenyl-substituted FR moieties are attached at the hydroxyl groups, and the phenyl-substituted pentane-1,4-diol-based flame retardant compound **506** is formed. This compound **506** is a flame retardant levulinic acid-based small molecule, which can be blended with a polymer to add flame retardancy to the polymer. It should be noted that reactions with phosphorus-based flame retardant molecules **204** and/or **206** and DMAP and/or a stoichiometric amount of an organic amine (such as triethylamine (NEt_3)), in a DCM solution can attach FR moieties to hydroxyl groups on any of the levulinic acid-based compounds disclosed herein that have hydroxyl groups (e.g., compounds **408**, **412**, **416**, **420**, **424**, and **428**). Further, it should be noted that an epoxy R group can be produced by reacting an allyl functional group **306** with a peroxide reagent, such as meta-chloroperoxybenzoic acid (mCPBA). Further, epoxy R groups **307** can ring open in reactions involving nucleophiles.

FIG. **5**B is a chemical reaction diagram illustrating a process **500-2** of forming R-functionalized and/or phenyl-substituted 4-hydroxypentanoic acid-derived flame retardant compounds **508**, according to some embodiments of the present disclosure. In this reaction, 4-hydroxypentanoic acid **408** is reacted with a phosphorus-based flame-retardant molecule **204** or **206** in two steps. Carrying out the reaction in multiple steps with different phosphorus-based flame-retardant molecules **204** or **206** allows the formation of monofunctionalized, difunctionalized, or phenyl-substituted 4-hydroxypentanoic acid-derived flame retardant compounds **508**. In the first step, an FR moiety with a functional group or phenyl (Ph) substituent represented by R' is added at the location of the hydroxyl group, and in the second step, FR moieties with functional groups or phenyl (Ph) substituents represented by R are added at the location of the carboxylic acid group.

In the first step, the selected phosphorus-based flame-retardant molecule **204** or **206** is reacted with 4-hydroxypentanoic acid **408** and catalytic dimethylaminopyridine (cat. DMAP) and/or a stoichiometric amount of an organic amine (such as triethylamine (NEt_3)), in a dichloromethane (DCM) solution. These reaction conditions cause the phosphorus-based flame retardant molecule **204** or **206** to react with the hydroxyl group on 4-hydroxypentanoic acid **408**, and attach an FR moiety. In the second step, the selected phosphorus-based flame-retardant molecule **204** or **206** is reacted with the product from the first step and magnesium oxide (MgO). These reaction conditions cause the phosphorus-based flame retardant molecule **204** or **206** to react with the carboxylic acid group on the product from the first step (and originally from 4-hydroxypentanoic acid **408**), and attach an FR moiety. Carrying out the syntheses of the 4-hydroxypentanoic acid-derived flame retardant compounds **508** in multiple steps allows the identity of the R and R' groups and the degree of functionality to be varied.

For example, if steps one and two are both carried out with a phenyl-substituted phosphorus-based flame retardant molecule **206**, compound **508** will be a phenyl-substituted flame retardant small molecule that can be blended with materials such as polymers to impart flame retardancy. Further, if steps one and two are both carried out with an R-functionalized flame-retardant phosphorus-based molecule **204**, compound **508** will be a difunctionalized flame retardant compound that can be a cross-linker in a polymer, or it can be polymerized to form a flame retardant polymer. The functional R or R' groups on the phosphorus-based molecule **204** can be varied between steps one and two, yielding a difunctionalized compound with different types of functional groups (e.g., one allyl R group **306** and one epoxy R' group **307**).

In additional examples, if step one is carried out with a phenyl-substituted phosphorus-based flame retardant molecule **206**, and step two is carried out with an R-functionalized phosphorus-based flame retardant molecule **204**, compound **508** will be a monofunctionalized flame retardant compound where the R group is an allyl **306** or epoxy **307** functional group (depending on the choice of R group on compound **204**), and where the R' group is a phenyl substituent. Further, carrying out step one with an R-functionalized phosphorus-based flame retardant molecule **204**, and step two with a phenyl-substituted phosphorus-based flame retardant molecule **206**, yields a monofunctionalized flame retardant compound **508** with the functionalization occurring at the R' site within flame retardant compound **508**. Monofunctionalized flame retardant compounds **508** can be polymerized, or bound to polymer chains, causing the polymer to be flame retardant.

FIG. **5**C is a chemical reaction diagram illustrating a process **500-3** of forming a monofunctionalized 4-((tert-butyldimethylsilyl)oxy)pentan-1-ol-derived flame retardant compound **512**, according to some embodiments of the present disclosure. Process **500-3** is carried out in three steps. In the first step, levulinic acid-derived 4-((tert-butyldimethylsilyl)oxy)pentan-1-ol **412** is reacted with an R-functionalized phosphorus-based compound **204** and catalytic dimethylaminopyridine (cat. DMAP) and/or a stoichiometric amount of an organic amine (such as triethylamine (NEt_3)), in dichloromethane (DCM). This step attaches an R-functionalized FR moiety at the hydroxyl group on 4-((tert-butyldimethylsilyl)oxy)pentan-1-ol **412**.

The second step is a deprotection reaction. In this step, tetra-n-butylammonium fluoride (TBAF) in THF is added to the reaction mixture. This deprotection exposes a secondary hydroxyl group, which is then reacted in the third step with a phenyl-substituted phosphorus-based compound **206** and cat. DMAP and/or a stoichiometric amount of an organic amine (such as triethylamine (NEt_3)), in DCM. The third step attaches a phenyl-substituted FR moiety to the newly exposed hydroxyl group, and forms the monofunctionalized 4-((tert-butyldimethylsilyl)oxy)pentan-1-ol-derived flame retardant compound **512**. In some embodiments, the phenyl-substituted flame retardant phosphorus-based compound **206** could be used in step one and the R-functionalized flame retardant phosphorus based compound **204** could be used in step two, producing a monofunctionalized compound with the R and Ph groups in the opposite positions.

FIG. **5**D is a chemical reaction diagram illustrating a process **500-4** of forming R-functionalized and/or phenyl-substituted 5-hydroxy-4-oxopentanoic acid-derived flame retardant compounds **516**, according to some embodiments of the present disclosure. In this reaction, 5-hydroxy-4-oxopentanoic acid **416** is reacted with a phosphorus-based flame-retardant molecule **204** or **206** in two steps. Similar to process **500-2**, carrying out the reaction in multiple steps with different phosphorus-based flame-retardant molecules **204** or **206** allows the formation of monofunctionalized, difunctionalized, or phenyl-substituted 5-hydroxy-4-oxopentanoic acid-derived flame retardant compounds **516**. In the first step, an FR moiety with a functional group or phenyl (Ph) substituent represented by R' is added at the location of the hydroxyl group, and in the second step, FR moieties with functional groups or phenyl (Ph) substituents represented by R are added at the location of the carboxylic acid group.

In the first step, the selected phosphorus-based flame-retardant molecule **204** or **206** is reacted with 5-hydroxy-4-oxopentanoic acid **416** and catalytic dimethylaminopyridine (cat. DMAP) and/or a stoichiometric amount of an organic amine (such as triethylamine (NEt_3)), in a dichloromethane (DCM) solution. These reaction conditions cause the phosphorus-based flame retardant molecule **204** or **206** to react with the hydroxyl group on 5-hydroxy-4-oxopentanoic acid **416**, and attach an FR moiety. In the second step, the selected phosphorus-based flame-retardant molecule **204** or **206** is reacted with the product from the first step and magnesium oxide (MgO). These reaction conditions cause the phosphorus-based flame retardant molecule **204** or **206** to react with the carboxylic acid group on the product from the first step (and originally from 5-hydroxy-4-oxopentanoic acid **416**), and attach an FR moiety. Carrying out the syntheses of the 5-hydroxy-4-oxopentanoic acid-derived flame retardant compounds **508** in multiple steps allows the identity of the R and R' groups and the degree of functionality to be varied.

For example, if steps one and two are both carried out with a phenyl-substituted phosphorus-based flame retardant molecule **206**, compound **516** will be a phenyl-substituted flame retardant small molecule that can be blended with materials such as polymers to impart flame retardancy. Further, if steps one and two are both carried out with an R-functionalized flame-retardant phosphorus-based molecule **204**, compound **516** will be a difunctionalized flame retardant compound that can be a cross-linker in a polymer, or it can be polymerized to form a flame retardant polymer. The functional R or R' groups on the phosphorus-based molecule **204** can be varied between steps one and two, yielding a difunctionalized compound with different types of functional groups (e.g., one allyl R group **306** and one epoxy R' group **307**).

In additional examples, if step one is carried out with a phenyl-substituted phosphorus-based flame retardant molecule **206**, and step two is carried out with an R-functionalized phosphorus-based flame retardant molecule **204**, compound **516** will be a monofunctionalized flame retardant compound where the R group is an allyl **306** or epoxy **307** functional group (depending on the choice of R group on compound **204**), and where the R' group is a phenyl substituent. Further, carrying out step one with an R-functionalized phosphorus-based flame retardant molecule **204**, and step two with a phenyl-substituted phosphorus-based flame retardant molecule **206**, yields a monofunctionalized flame retardant compound **516** with the functionalization occurring at the R' site within flame retardant compound **516**. Monofunctionalized flame retardant compounds **516** can be polymerized, or bound to polymer chains, causing the polymer to be flame retardant.

FIG. **5**E is a chemical reaction diagram illustrating a process **500-5** of forming R-functionalized and/or phenyl-substituted 4,5-dihydroxypentanoic acid-derived flame retardant compounds **520**, according to some embodiments of the present disclosure. In this reaction, 4,5-dihydroxypentanoic acid **420** is reacted with a phosphorus-based flame-retardant molecule **204** or **206** in two steps. Carrying out the reaction in multiple steps with different phosphorus-based flame-retardant molecules **204** or **206** allows the formation of monofunctionalized, difunctionalized, trifunctionalized, or phenyl-substituted 4,5-dihydroxypentanoic acid-derived flame retardant compounds **520**. In the first step, FR moieties with functional groups or phenyl (Ph) substituents represented by R' are added at the locations of the hydroxyl groups, and in the second step, an FR moiety with a functional group or phenyl (Ph) substituent represented by R is added at the location of the carboxylic acid group.

In the first step, the selected phosphorus-based flame-retardant molecule **204** or **206** is reacted with 4,5-dihydroxypentanoic acid **420** and catalytic dimethylaminopyridine (cat. DMAP) and/or a stoichiometric amount of an organic amine (such as triethylamine (NEt_3)), in a dichloromethane (DCM) solution. These reaction conditions cause the phosphorus-based flame retardant molecule **204** or **206** to react with the hydroxyl groups on 4,5-dihydroxypentanoic acid **420**, and attach FR moieties. In the second step, the selected phosphorus-based flame-retardant molecule **204** or **206** is reacted with the product from the first step and magnesium oxide. These reaction conditions cause the phosphorus-based flame retardant molecule **204** or **206** to react with the carboxylic acid group on 4,5-dihydroxypentanoic acid **420**, and attach an FR moiety. Carrying out the syntheses of the 4,5-dihydroxypentanoic acid-derived flame retardant compounds **520** in multiple steps allows the identity of the R and R' groups and the degree of functionality to be varied.

For example, if steps one and two are both carried out with a phenyl-substituted phosphorus-based flame retardant molecule **206**, compound **520** will be a phenyl-substituted flame retardant small molecule that can be blended with materials such as polymers to impart flame retardancy. Further, if steps one and two are both carried out with an R-functionalized flame-retardant phosphorus-based molecule **204**, compound **520** will be a trifunctionalized flame retardant compound that can be a cross-linker in a polymer, or it can be polymerized to form a flame retardant polymer. The functional R or R' groups on the phosphorus-based molecule **204** can be varied between steps one and two, yielding a trifunctionalized compound with different types of functional groups (e.g., one allyl R group **306** and two epoxy R' groups **307**).

In some embodiments, varying the R and R' groups on the 4,5-dihydroxypentanoic acid-derived flame retardant compound **520** can result in compounds with different degrees of functionality. For example, if step one is carried out with an R-functionalized phosphorus-based flame retardant molecule **204**, and step two is carried out with a phenyl-substituted phosphorus-based flame retardant molecule **206**, compound **520** will be a difunctionalized flame retardant compound where the R' groups are each an allyl **306** or epoxy **307** functional group (depending on the choice of R group on compound **204**), and where the R group is a phenyl substituent. Like a trifunctionalized compound **520**, a difunctionalized flame retardant compound **520** can be a cross-linker, or it can be polymerized. Further, carrying out step one with a phenyl-substituted phosphorus-based flame retardant molecule **206**, and step two with an R-functionalized phosphorus-based flame retardant molecule **204**, yields a monofunctionalized flame retardant compound **520**. Monofunctionalized flame retardant compounds **520** can be polymerized, or bound to polymer chains, causing the polymer to be flame retardant.

FIG. **5**F is a chemical reaction diagram illustrating a process **500-6** of forming a trifunctionalized pentane-1,2,5-triol-derived flame retardant compound **524** and a phenyl-substituted pentane-1,2,5-triol-derived flame retardant compound **526**, according to some embodiments of the present disclosure. In both reactions, pentane-1,2,5-triol **424** is reacted with a phosphorus-based flame-retardant molecule **204** or **206** and catalytic dimethylaminopyridine (cat. DMAP) and/or a stoichiometric amount of an organic amine (such as triethylamine (NEt_3)), in a dichloromethane (DCM) solution. When the reaction is carried out with an R-functionalized phosphorus-based compound **204**, allyl-**306** or epoxy-**307** functionalized FR moieties are attached at the hydroxyl groups on pentane-1,2,5-triol **424**. This reaction forms the trifunctionalized pentane-1,2,5-triol-derived flame retardant compound **524**. This compound **524** is a flame retardant levulinic acid-based compound that can be polymerized or act as a cross-linker in another polymer. Its inclusion in a polymer, either as a monomer or a cross-linker, causes the polymer to be flame retardant.

If process **500-6** is carried out with a phenyl-substituted phosphorus-based compound **206**, phenyl-substituted FR moieties are attached at the hydroxyl groups, and the phenyl-substituted pentane-1,2,5-triol-derived flame retardant compound **526** is formed. This compound **526** is a flame retardant levulinic acid-based small molecule, which can be blended with a polymer to impart flame retardancy.

FIG. **5**G is a chemical reaction diagram illustrating a process **500-7** of forming a monofunctionalized 3-(2,2-dimethyl-1,3-dioxolan-4-yl)propan-1-ol-derived flame retardant compound **528**, according to some embodiments of the present disclosure. Process **500-7** is carried out in three steps. In the first step, levulinic acid-derived 3-(2,2-dimethyl-1,3-dioxolan-4-yl)propan-1-ol **428** is reacted with an R-functionalized phosphorus-based compound **204** and catalytic dimethylaminopyridine (cat. DMAP) and/or a stoichiometric amount of an organic amine (such as triethylamine (NEt_3)), in dichloromethane (DCM). This step attaches an R-functionalized FR moiety at the hydroxyl group on 3-(2,2-dimethyl-1,3-dioxolan-4-yl)propan-1-ol **428**.

The second step is a deprotection reaction. This step is a ring-opening deprotection reaction using an acid such as p-toluenesulfonic acid (p-TsOH) or hydrochloric acid (HCl). The addition of the acid to the reaction mixture exposes two hydroxyl groups, which are then reacted in the third step with a phenyl-substituted phosphorus-based compound **206** and cat. DMAP and/or a stoichiometric amount of an organic amine (such as triethylamine (NEt_3)), in DCM. The third step attaches phenyl-substituted FR moieties to the newly exposed hydroxyl groups, and forms the monofunctionalized 3-(2,2-dimethyl-1,3-dioxolan-4-yl)propan-1-ol-derived flame retardant compound **528**. In some embodiments, the phenyl-substituted flame retardant phosphorus-based compound **206** could be used in step one and the R-functionalized flame retardant phosphorus based compound **204** could be used in step two, producing a difunctionalized compound.

FIG. **5**H is a chemical reaction diagram illustrating a process **500-8** of forming a propylene carbonate-functionalized levulinic acid-based flame retardant compound **532**, according to some embodiments of the present disclosure. In this reaction, the difunctionalized levulinic acid-based flame retardant compound **504** having epoxy R groups **307** is combined with lithium bromide (LiBr). Carbon dioxide (CO_2) is added to the mixture, yielding the propylene carbonate-functionalized flame retardant levulinic acid-based compound **532**. It should be noted that the reaction between the epoxy R groups **307**, LiBr, and CO_2 can be carried out with any of the epoxy-functionalized compounds disclosed herein, including epoxy-functionalized versions of **508**, **512**, **516**, **520**, **524**, and **528**. This reaction converts any epoxy R groups **307** to propylene carbonate R groups **534**.

FIG. **6**A is a chemical reaction diagram illustrating a process **600-1** of forming phenyl-substituted thioether-linked flame retardant pentane-1,4-diol-based compounds **604**, according to some embodiments of the present disclosure. The process **600-1** can be carried out under reaction conditions A, B, or C. Each of these reaction conditions is a thiol-ene reaction between the difunctionalized levulinic acid-based flame retardant compound **504** having allyl R groups **306** and a phenyl-substituted flame retardant thiol molecule **328**, **336**, or **348**. Each thiol molecule binds to an allyl group on the pentane-1,4-diol-based precursor **504**. The syntheses and structures of the phenyl-substituted flame retardant thiol molecules are discussed in greater detail with regard to FIGS. **3**C and **3**D. The thiols provide phenyl-substituted thioether groups, which are also referred to "Ph-R"—S" groups herein. The phenyl-substituted Ph-R"—

S-linked flame-retardant levulinic acid-based compounds **604** can be blended with polymers to impart flame retardancy.

Under thiol-ene reaction conditions A, the difunctionalized pentane-1,4-diol-based flame retardant compound **504** having allyl R groups **306** is reacted with the phenyl-substituted carboxylic acid-derived flame-retardant thiol molecule **328** under UV light in a methanol (MeOH) solution. The resulting Ph-R"—S-linked flame-retardant levulinic acid-based compound **604** has thioether groups **608** that correspond to the carboxylic acid-derived flame-retardant thiol molecule **328**.

Under thiol-ene reaction conditions B, the difunctionalized pentane-1,4-diol-based flame retardant compound **504** having allyl R groups **306** is reacted with the phenyl-substituted hydroxy-derived flame retardant thiol molecule **336** under UV light. The resulting Ph-R"—S-linked flame-retardant levulinic acid-based compound **604** has thioether groups **612** that correspond to the hydroxy-derived flame retardant thiol molecule **336**.

Under thiol-ene reaction conditions C, the difunctionalized pentane-1,4-diol-based flame retardant compound **504** having allyl R groups **306** is reacted with the phenyl-substituted amine-derived flame retardant thiol molecule **348** under UV light in a pH 9 methanol solution. The resulting Ph-R"—S-linked flame-retardant levulinic acid-based compound **604** has thioether groups **616** that correspond to the amine-derived flame retardant thiol molecule **348**.

FIG. **6**B is a chemical reaction diagram illustrating a process **600-2** of forming difunctionalized thioether-linked flame retardant pentane-1,4-diol-based compounds **624**, according to some embodiments of the present disclosure. The process **600-2** is carried out under reaction conditions A, B, or C. Each of these reaction conditions is a thiol-ene reaction between the difunctionalized pentane-1,4-diol-based flame retardant compound **504** having allyl R groups **306** and a thiol molecule, which can be 3-mercaptopropionate **352**, 2-mercaptoethanol **356**, or cysteamine hydrochloride (HCl) **360**. The thiols provide R"-functionalized thioether groups, which are also referred to "R"-S" groups herein. Each thiol molecule reacts with an allyl group on the pentane-1,4-diol-based precursor **504**, forming difunctionalized thioether-linked levulinic acid-based compounds **624**. These compounds **624** can bind to polymers, and act as cross-linkers, causing the polymers to be flame retardant.

Under thiol-ene reaction conditions A, the difunctionalized pentane-1,4-diol-based flame retardant compound **504** having allyl R groups **306** is reacted with 3-mercaptopropionate **352** under UV light in a methanol (MeOH) solution. The resulting R"—S-linked flame-retardant levulinic acid-based compound **624** has thioether groups **628** that correspond to the 3-mercaptopropionate **352**. Under thiol-ene reaction conditions B, the difunctionalized pentane-1,4-diol-based flame retardant compound **504** having allyl **306** R groups is reacted with 2-mercaptoethanol **356** under UV light. The resulting R"—S-linked flame-retardant levulinic acid-based compound **624** has thioether groups **632** that correspond to the 2-mercaptoethanol **356**. Under thiol-ene reaction conditions C, the difunctionalized pentane-1,4-diol-based flame retardant compound **504** having allyl R groups **306** is reacted with cysteamine HCl **360** under UV light in a pH 9 methanol solution. The resulting R"—S-linked flame-retardant levulinic acid-based compound **624** has thioether groups **636** that correspond to the cysteamine HCl **360**.

The reactions **600-1** and **600-2** between the allyl R groups **306** on the difunctionalized pentane-1,4-diol-based flame retardant compound **504** and the thiol molecules **328**, **336**, **348**, **352**, **356**, or **360** can be carried out with any of the allyl-functionalized compounds disclosed herein, including allyl-functionalized versions of **508**, **512**, **516**, **520**, **524**, and **528**. The reactions attach the corresponding thioether groups **608**, **612**, **616**, **628**, **632**, or **636** at the locations of the allyl functional groups. This can result in different degrees of functionalization, which is illustrated in the examples of FIGS. **6**C and **6**D.

FIG. **6**C is a chemical reaction diagram illustrating a process **600-3** of forming phenyl-substituted thioether-linked flame retardant 4,5-dihydroxypentanoic acid-derived flame retardant compounds **640**, according to some embodiments of the present disclosure. The process **600-3** is carried out under reaction conditions A, B, or C. These reaction conditions are substantially similar to those described with respect to process **600-1** in FIG. **6**A. Each reaction is a thiol-ene reaction between the trifunctionalized 4,5-dihydroxypentanoic acid-derived flame retardant compound **520** having allyl R and R' groups **306** and a phenyl-substituted flame retardant thiol molecule **328**, **336**, or **348**. Each thiol molecule binds to an allyl group on the 4,5-dihydroxypentanoic acid-derived precursor **520**. The resulting phenyl-substituted Ph-R"—S-linked flame-retardant 4,5-dihydroxypentanoic acid-derived flame retardant compounds **640** can be blended with polymers to impart flame retardancy. Varying different degrees of functionalization can result from performing process **600-3** using a 4,5-dihydroxypentanoic acid-derived precursor **520** with an allyl R group **306** and non-allyl R' groups (such as phenyl groups), or vice versa (a 4,5-dihydroxypentanoic acid-derived precursor **520** with a non-allyl R group (such as phenyl groups) and allyl R' groups **306**). Accordingly, the thiol-ene reaction will occur only at the allyl R group **306** and not the non-allyl R' groups, or vice versa (at the allyl R' groups **306**, and not at the non-allyl R group). Variations of process **600-3** can yield resulting Ph-R"—S-linked flame-retardant levulinic acid-based compounds **620** with one, two, or three of thioether groups **608**, **612**, or **616** corresponding to the number of allyl groups present in precursor **520** (based on the identities of the R and R' groups).

FIG. **6**D is a chemical reaction diagram illustrating a process **600-4** of forming trifunctionalized thioether-linked flame retardant 4,5-dihydroxypentanoic acid-derived compounds **644**, according to some embodiments of the present disclosure. The process **600-4** is carried out under reaction conditions A, B, or C. These reaction conditions are substantially similar to those described with respect to process **600-2** in FIG. **6**B. Each reaction is a thiol-ene reaction between the trifunctionalized 4,5-dihydroxypentanoic acid-derived flame retardant compound **520** having allyl R and R' groups **306** and a thiol molecule, which can be 3-mercaptopropionate **352**, 2-mercaptoethanol **356**, or cysteamine hydrochloride (HCl) **360**. Each thiol molecule reacts with an allyl group on the 4,5-dihydroxypentanoic acid-derived precursor **520**, forming trifunctionalized thioether-linked 4,5-dihydroxypentanoic acid-derived compounds **644**. These compounds **644** can bind to polymers, and act as cross-linkers, causing the polymers to be flame retardant. Varying different degrees of functionalization can result from performing process **600-4** using a 4,5-dihydroxypentanoic acid-derived precursor **520** with an allyl R group **306** and non-allyl R' groups (such as phenyl groups), or vice versa (a 4,5-dihydroxypentanoic acid-derived precursor **520** with a non-allyl R group (such as phenyl groups) and allyl R' groups **306**). Accordingly, the thiol-ene reaction will occur only at the allyl R group **306** and not the non-allyl R' groups, or vice versa (at the allyl R' groups **306** and not at the non-allyl R group). Variations of process **600-4** can yield resulting R"—S-linked flame-retardant levulinic acid-based compounds **644** with one, two, or three of thioether groups **628**, **632**, or **636** corresponding to the number of allyl groups present in precursor **520** (based on the identities of the R and R' groups).

The processes of forming the flame retardant levulinic acid-based compounds illustrated herein can be carried out with different combinations of phosphorus-based flame retardant molecules **204** and **206**. In some embodiments, these processes can be carried out with either all phosphate-based flame retardant molecules (**204-1** and/or **206-1**) or all phosphonate-based flame retardant molecules (**204-2** and/or **206-2**). In other embodiments, a mixture of both phosphate-phosphonate-based flame retardant molecules can be used. Carrying out these processes with a mixture of phosphate- and phosphonate-based molecules (**206-1/206-2** and/or **204-1/204-2**) can result in the production of flame retardant levulinic acid-based monomers with both phosphoryl and phosphonyl FR groups.

However, in some instances, adding a mixture of phosphate- and phosphonate-based molecules (**206-1/206-2** or **204-1/204-2**) can result in the production of flame retardant levulinic acid-based monomers with all phosphoryl or all phosphonyl FR moieties. Additionally, adding a mixture of phosphate- and phosphonate-based molecules (**206-1/206-2** or **204-1/204-2**) to the reaction can yield a mixture of products that includes some combination of flame retardant levulinic acid-based monomers with either all phosphoryl or all phosphonyl FR groups and flame retardant levulinic acid-based monomers with both phosphoryl and phosphonyl FR groups.

FIG. **7**A is a diagrammatic representation of the structures **700** of generic R-functionalized levulinic acid-based flame retardant monomers **704**, **708**, and **712**, according to some embodiments of the present disclosure. The monomers are trifunctionalized flame retardant levulinic acid-based compounds **704** (e.g., compounds **520** and **524**), difunctionalized flame retardant levulinic acid-based compounds **708** (e.g., compounds **504**, **508**, **516**, **528**, and **532**), and monofunctionalized flame retardant levulinic acid-based compounds **712** (e.g., compounds **512** and **528**). Examples of compounds represented by these structures **700** are discussed in greater detail with respect to FIGS. **5**A-**5**H. The R-functionalized levulinic acid-based compounds **700** can be polymerized to form flame retardant levulinic acid-based polymers. Each structure shows only the ligands with R functional groups (e.g., allyl, epoxy, or propylene carbonate). An oval labeled "LD" represents the levulinic acid-derivative core of each monomer.

FIG. **7**B is a chemical reaction diagram illustrating processes **714-1**, **714-2**, and **714-3** of synthesizing flame retardant levulinic acid-based polymers **716**, **720**, and **724** from flame retardant levulinic acid-based compounds, according to some embodiments of the present disclosure. The reactions illustrated herein are prophetic examples of polymers that can be synthesized from the flame retardant levulinic acid-based monomers, but other polymers can be produced as well (e.g., by changing reaction conditions, co-monomers, R groups, etc.).

Processes **714-1-714-3** illustrate the polymerization of difunctionalized flame retardant levulinic acid-based monomers **708** only. However, it should be noted that each of these polymerization reactions can also be carried out with the trifunctionalized flame retardant levulinic acid-based monomers **704**. Additionally, processes **714-1** and **714-3** can be carried out with the monofunctionalized flame retardant levulinic acid-based monomers **712**. Further, in some embodiments, the polymerization reactions are carried out with a combination of both difunctionalized flame retardant levulinic acid-based monomers **708** and trifunctionalized flame retardant levulinic acid-based monomers **704**, both difunctionalized flame retardant levulinic acid-based monomers **708** and monofunctionalized flame retardant levulinic acid-based monomers **712**, both trifunctionalized flame retardant levulinic acid-based monomers **704** and monofunctionalized flame retardant levulinic acid-based monomers **712**, or a combination of monomers that includes tri-, di-, and monofunctionalized monomers in any ratio.

In process **714-1**, allyl-derived flame retardant levulinic acid-based polymers **716** are formed from difunctionalized flame retardant levulinic acid-based compounds **708** having allyl R groups **306**. The difunctionalized flame retardant levulinic acid-based compound **708** is reacted with a Ziegler-Natta catalyst. Ziegler-Natta catalysts catalyze the polymerization of 1-alkenes. Examples of these catalysts can include heterogeneous Ziegler-Natta catalysts based on titanium compounds and homogeneous Ziegler-Natta catalysts based on complexes of titanium, zirconium, or hafnium. Heterogeneous and homogeneous Ziegler-Natta catalysts can be used in combination with organoaluminum co-catalysts in some embodiments.

In process **714-2**, epoxy-derived flame retardant levulinic acid-based polymers **720** are formed from difunctionalized flame retardant levulinic acid-based monomers **708** having epoxy R groups **307**. The difunctionalized flame retardant levulinic acid-based compound **708** is reacted with a base and a second monomer **706**. The second monomer **706** is a compound with at least two hydroxyl (OH) groups or at least two amino (NH_2) groups (e.g., a diol, polyol, diamine, polyamine, etc.). These compounds **706** are illustrated as a gray oval with attached A groups. The A group represents a hydroxyl group or an amino group. It should be noted that, while two A groups are illustrated herein, there are more than two A groups in some embodiments. In some embodiments, compounds **706** can be diol or diamine versions of difunctionalized thioether-linked flame retardant pentane-1,4-diol-based compounds **624**; diol, polyol, diamine, or polyamine versions of trifunctionalized thioether-linked flame retardant 4,5-dihydroxypentanoic acid-derived compounds **644**; or other diol, polyol, diamine, or polyamine thioether-linked flame retardant levulinic acid derivatives. Additionally, in some embodiments, the difunctionalized levulinic acid-based compound **708** having epoxy R groups **307** self-polymerizes under basic conditions. In these instances, the reaction does not include the second monomer **706**.

In process **714-3**, propylene carbonate-derived flame retardant levulinic acid-based polymers **724** are formed from difunctionalized flame retardant levulinic acid-based monomers having propylene carbonate R groups **529**. The difunctionalized flame retardant levulinic acid-based monomer **708** having propylene carbonate R groups **529** is reacted in a ring-opening polymerization initiated by a base. Examples of bases that can be used as initiators can include potassium hydroxide (KOH), sodium hydroxide (NaOH), lithium hydroxide (LiOH), 1,8-diazabicyclo(5.4.0)undec-7-ene (DBU), triazabicyclodecene (TBD), etc.

In addition to the polymers illustrated in FIG. **7**B, the flame retardant levulinic acid-based compounds disclosed herein can be used in the synthesis of other flame retardant polymers in some embodiments. An array of classes of flame retardant polymers can be made with different combinations of monomers. These polymerization processes are in accordance with polymer chemistry platforms that can include polyhydroxyurethanes, polycarbonates, polymers obtained by radical polymerization, polyurethanes, polyesters, polyacrylates, epoxy resins, polyimides, polyureas, polyamides, poly(vinyl-esters), etc.

One example of an application of polymers that incorporate flame retardant levulinic acid-based compounds is in plastics used in electronics hardware, such as integrated circuit packages. Additional applications can include acoustic dampening, cushioning, plastics, synthetic fibers, insulation, etc. The flame retardant levulinic acid-based compounds can also be used to make adhesives such as bio-adhesives, elastomers, thermoplastics, emulsions, thermosets, etc. Further, materials containing the flame retardant levulinic acid-based compounds can be incorporated into various devices with electronic components that can include printed circuit boards (PCBs), semiconductors, transistors, optoelectronics, capacitors, resistors, chip carriers, etc.

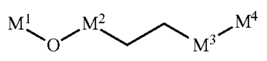
Resins for printed circuit boards (PCBs) can be made flame retardant by incorporating polymers that include levulinic acid-based flame retardant compounds. PCBs are electrical circuits that can be found in most types of electronic device, and they support and electronically connect electrical components in the device. PCBs are formed by etching a copper conductive layer laminated onto an insulating substrate. The insulating substrate can be a laminate comprising a resin and a fiber. Many resins in PCBs contain a polymer, such as an epoxy, a polyhydroxyurethane, a polycarbonate, a polyester, a polyacrylate, a polyimide, a polyamide, a polyurea, a poly(vinyl-ester), etc. Using polymers that incorporate the flame retardant levulinic acid-based compounds can prevent the PCB from catching fire when exposed to high temperature environments or electrical power overloads.

It should be noted that, in some embodiments, the compounds described herein can contain one or more chiral centers. These can include racemic mixtures, diastereomers, enantiomers, and mixtures containing one or more stereoisomer. Further, the disclosed compounds can encompass racemic forms of the compounds in addition to individual stereoisomers, as well as mixtures containing any of these.

The synthetic processes discussed herein and their accompanying drawings are not to be construed as limiting. One skilled in the art would recognize that a variety of synthetic reactions may be used that vary in reaction conditions, components, methods, etc., which ultimately generate one or both of flame retardant levulinic acid-based compounds and their corresponding polymer derivatives. In addition, the reaction conditions can optionally be changed over the course of a process. Further, in some embodiments, processes can be added or omitted while still remaining within the scope of the disclosure, as will be understood by a person of ordinary skill in the art.

What is claimed is:

1. A flame retardant levulinic acid-based compound with a formula of:



wherein M^1 is a moiety selected from a group consisting of a phenyl-substituted flame retardant group and an R-functionalized flame retardant group;

wherein M^2 is a methylene bridge group;

wherein M^3 is a moiety selected from a group consisting of the carbonyl group, a methine group with an ether-linked phenyl-substituted flame retardant group, and a methine group with an ether-linked R-functionalized flame retardant group;

wherein M^4 is a methyl group when M^3 is the methine group with the ether-linked phenyl-substituted flame retardant group or the methine group with the ether-linked R-functionalized flame retardant group;

wherein M^4 is a moiety selected from a group consisting of a methyl group, a methylene bridge to an ether-linked phenyl-substituted flame retardant group, and a methylene bridge to an ether-linked R-functionalized flame retardant group when M^3 is the carbonyl group; and

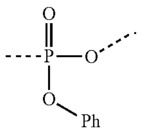
wherein when the selection of M^4 is the methylene bridge to the ether-linked phenyl-substituted flame retardant group or the methylene bridge to the ether-linked R-functionalized flame retardant group and when the selection of M^3 is the methine group with the ether-linked phenyl-substituted flame retardant group or the methine group with the ether-linked R-functionalized flame retardant group, the selection of the ether-linked phenyl-substituted flame retardant group or the ether-linked R-functionalized flame retardant group of M^4 limits the selection of the ether-linked phenyl-substituted flame retardant group or the ether-linked R-functionalized flame retardant group of M^3.

2. The flame retardant levulinic acid-based compound of claim **1**, wherein the R-functionalized flame retardant group has an allyl functional group.

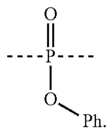
3. The flame retardant levulinic acid-based compound of claim **1**, wherein the R-functionalized flame retardant group has an epoxy functional group.

4. The flame retardant levulinic acid-based compound of claim **1**, wherein the R-functionalized flame retardant group has a propylene carbonate functional group.

5. The flame retardant levulinic acid-based compound of claim **1**, wherein at least one flame retardant group selected from the group consisting of the phenyl-substituted flame retardant group and the R-functionalized flame retardant group, has at least one phosphoryl moiety with a formula of:



6. The flame retardant levulinic acid-based compound of claim **1**, wherein at least one flame retardant group selected from the group consisting of the phenyl-substituted flame retardant group and the R-functionalized flame retardant group, has at least one phosphonyl moiety with a formula of:

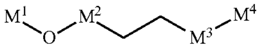


7. The flame retardant levulinic acid-based compound of claim **1**, wherein the flame retardant levulinic acid-based compound is incorporated into a polymer to form a flame retardant polymer.

8. An article of manufacture, comprising:

a material containing a flame retardant levulinic acid-based polymer,

wherein the flame retardant levulinic acid-based polymer is a polymer that includes a flame retardant levulinic acid-based compound, and wherein the flame retardant levulinic acid-based compound has a formula of:



wherein M^1 is a moiety selected from a group consisting of a phenyl-substituted flame retardant group and an R-functionalized flame retardant group;

wherein M^2 is a methylene bridge group;

wherein M^3 is a moiety selected from a group consisting of the carbonyl group, a methine group with an ether-linked phenyl-substituted flame retardant group, and a methine group with an ether-linked R-functionalized flame retardant group; and

wherein M^4 is a moiety selected from a group consisting of a methyl group, a methylene bridge to an ether-linked phenyl-substituted flame retardant group, a methylene bridge to an ether-linked R-functionalized flame retardant group, a phenyl-substituent, a thioether-linked phenyl-substituted flame retardant group, and a thioether-linked R-substituted flame retardant group.

9. The article of manufacture of claim **8**, further comprising an electronic component.

10. The article of manufacture of claim **8**, wherein the material is a plastic for integrated circuit packaging.

11. The article of manufacture of claim **8**, wherein the material is an adhesive.

12. The article of manufacture of claim **8**, wherein the material is a resin for a printed circuit boards (PCB).

13. The article of manufacture of claim **12**, wherein the resin is part of an insulating substrate in the PCB.

14. The article of manufacture of claim **8**,

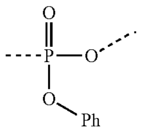
wherein M^4 is a methyl group when M^3 is the methine group with the ether-linked phenyl-substituted flame retardant group or the methine group with the ether-linked R-functionalized flame retardant group; and

wherein when the selection of M^4 is the methylene bridge to the ether-linked phenyl-substituted flame retardant group or the methylene bridge to the ether-linked R-functionalized flame retardant group and when the selection of M^3 is the methine group with the ether-linked phenyl-substituted flame retardant group or the methine group with the ether-linked R-functionalized flame retardant group, the selection of the ether-linked phenyl-substituted flame retardant group or the ether-linked R-functionalized flame retardant group of M^4 limits the selection of the ether-linked phenyl-substituted flame retardant group or the ether-linked R-functionalized flame retardant group of M^3.

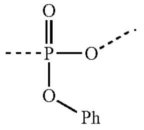
15. The article of manufacture of claim **14**, wherein the R-functionalized flame retardant group has an epoxy functional group.

16. The article of manufacture of claim **14**, wherein the R-functionalized flame retardant group has a propylene carbonate functional group.

17. The article of manufacture of claim **14**, wherein at least one flame retardant group selected from the group consisting of the phenyl-substituted flame retardant group and the R-functionalized flame retardant group, has at least one phosphoryl moiety with a formula of:



18. The article of manufacture of claim **14**, wherein at least one flame retardant group selected from the group consisting of the phenyl-substituted flame retardant group and the R-functionalized flame retardant group, has at least one phosphonyl moiety with a formula of:



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