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Review

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Catalytic Hydrogenation of Squalene to Squalane

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ABSTRACT: Full hydrogenation of squalene, a natural product, affords squalane, a saturated hydrocarbon whose exceptional properties make it the best emollient known to the cosmetic industry. As new methods to obtain squalene are being developed that replace the use of non-sustainable sources, the development of better hydrogenation processes becomes increasingly important. This study highlights recent progress and identifies open opportunities for further progress.

INTRODUCTION

First introduced as hemollient in the early 1950s by the French cosmetic ingredients company Laserson & Sabetay,[1] the fully saturated hydrocarbon squalane (2,6,10,15,19,23-hexamethyltetracosane, $C_{30}H_{62}$) is obtained through saturation of the six isolated double bonds in the highly unsaturated all-*trans* linear squalene (2,6,10,15,19,23-hexamethyl-2,6,10,14,18,22-tetracosahexaene) (Figure 1). The hydrogenation of squalene to dodecahydrosqualene over a palladium catalyst under hydrogen presseure was reported by Tsujimoto, who also dubbed the molecule, as early as 1916.[2]

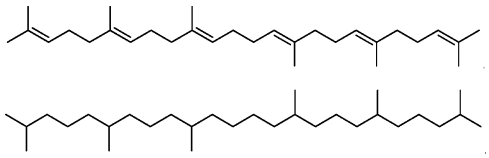

Figure 1. Chemical structures of squalene (top) and squalane (bottom).

Squalene and squalane are components of human sebum (comprising 13 and 2.5%, respectively).[3] The squalene molecule, indeed, plays a crucial role in human steroid synthesis, particularly in the biosynthesis of cholesterol.[4] Clear, colorless, odorless, tasteless, very stable, nontoxic, and nonirritant squalane oil is an exceptional emollient with a distinct ability to penetrate the human skin by acting as a liquid vehicle (without feeling greasy), causing skin hydration and increasing the percutaneous absorption of other active substances.[5]

First trade named Cosbiol, shark liver oil derived squalane was readily adopted by cosmetic formulators to produce formulations present in emollient and moisturizing creams, makeup, lipstick, and nail and hair personal care products.[6] Squalane oil, indeed, is smoothly emulsified in all types of formulations while being largely compatibile with other ingredients; additionally, it is resistant to oxidation, and its use does not require preservatives (often toxic, such as in the case of parabens).

Because of its non-sustainable and expensive sources, however, squalane use has decreased from 7500 tons to 2500 tons in the past decade, with recent selling prices around $30 per liter.[7] Following environmental protests and bans on shark hunting for cosmetic ends, many cosmetic companies today carry out isotopic analysis[8] of commercial samples, both in raw materials and in finished cosmetic formulations, to verify the origin of squalane as well as to detect adulteration of phytosqualane with squalane of shark origin.

A 2012 investigation[9] concluded that the cosmetic industry was still being largely supplied with animal squalane, with around 90% of the world's shark liver oil production feeding the needs of the cosmetics industry (which corresponds to 2.7 million deep-sea sharks caught every year for the 2500 tons squalane used in the global market).

Estimates from the first sugar cane phytosqualane manufacturer, on the other hand, point to a 2012 global squalane market share comprising 46% olive oil, 44% shark liver oil, and 10% new sugar cane-derived squalane.[10]

Whatever squalene's origin, fully saturated squalane for cosmetic use needs to have a more than 92% concentration and an iodine value lower than 1.00 (and preferably <0.10). Such high purity levels, with the commercial catalysts currently in use (see below) requiring relatively harsh conditions and extensive purification of the hydrogenated product, add cost to the product.

The current manufacturing process for hydrogenation, indeed, accounts for about 40% of the overall production cost of squalane.[14] As phytosqualane replaces squalane of animal origin (see below), new hydrogenation processes running at lower pressure and temperature are required to lower the cost of producing squalane. In the following, after discussing the sources of squalene, we describe the state of the art for current hydrogenation technology and identify opportunities for improvement.

SOURCES OF SQUALENE

For decades, the main source of squalene has been liver oil from small, deep sea sharks. The livers from approximately 3000 sharks are typically required to produce 1 ton of squalene. Squalene, with a purity of >98%, is obtained directly from shark liver oil after a single distillation phase under vacuum at temperatures of 200−230 °C. The massive hunting and

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Table 1. Composition of Squalane Commercial Samples of Different Origin[a]

	shark squalane	olive oil squalane	sugar cane squalane
squalane content	98–99%	82–94%	92–93%
impurities	not significant	sterol esters and paraffins	squalane isomer (isosqualane)

[a]Adapted with permission from ref 6. Copyright 2013 BGM Editions.

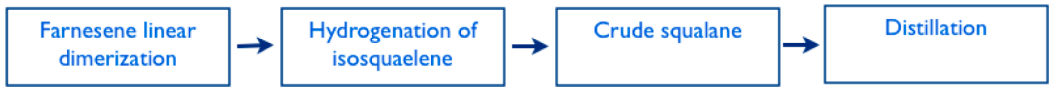

Figure 2. Process flow diagram for sugar-derived squalane. Adapted with permission from ref 17. Copyright 2014 Allured Buisness Media.

depletion of the deep sea shark population mentioned above led the European Union to reduce the fishing of deep sea species by drastic quotas established in the late 1990s.[11] Cosmetic companies then partly switched to squalane obtained from olive oil, which has a squalene content of 0.4–0.6%.[12]

In the late 1980s, researchers at Hispano Quìmica (now a branch of BASF) developed a method for the production of squalene from olive oil.[13] Because of its low concentration, extraction of squalene directly from olive oil is not economically convenient. Gas effluents, called deodorization distillates (DD) or oil physical refining condensates (OPRCs), recovered by condensation of the oil's unsaponifiable portion are instead used in place of virgin oil.

In detail, 100–300 g of squalene is obtained per kilogram of distillate deodorizer oil.[14] Two extraction processes are alternatively used. One is based on esterification of distilled fatty acids to obtain triglycerides, from which squalene with a high level of purity (>95%) is separated via high vacuum distillation. The other involves the extraction of the unsaponifiable fraction with hexane to afford squalene with a maximum purity of 82–83% (rich in saturated paraffin extracted by the solvent).

For comparison, some 70 h of processing is required to obtain olive oil squalene with a purity higher than 92%, whereas only 10 h is required to obtain shark squalene with a purity higher than 98%. By also taking into account that one hectare of land can produce up to 50 kg of squalane from olive oil byproducts, this explains why phytosqualane has consistently been >30% more expensive than shark squalane.[15]

Furthermore, the amounts of olive OPRCs and DDs that, for the last 15 years, have offered a unique, suitable option to replace shark squalene are limited and are not sufficient to replace squalene of animal origin. A major advance, therefore, was the recent commercialization of phytosqualane obtained from the 15 carbon sesquiterpene *trans-β*-farnesene, which, in turn, is derived from sugar cane sucrose fermentation over genetically modified *Saccharomyces cerevisiae* yeast strains (Figure 2).[16] Farnesene is first converted into isosqualene via catalytic dimerization over a Pd catalyst, and isosqualene is subequently hydrogenated in situ to squalane, producing a composition comprising 92–93% squalane and about 4% isosqualane.[17]

Similarly, the most recent methods for the production of phytosqualane from olive oil involve in situ hydrogenation of the as-obtained squalene, avoiding the need to isolate lipophilic and oxidatively unstable squalene. For example, a Spanish patent application[18] describes a process for the production of vegetable squalane in which the acidic pressing residue from the production of olive oil freed from fatty acids by distillation and saponification is hydrogenated, removing the paraffins by freezing to obtain pure phytosqualane by distillation.

Similarly, a Japanese patent application[19] describes a process for the production of squalane in which the fraction accumulating in the purification of olive oil by distillation, again freed from free fatty acids, is hydrogenated in situ to afford 93% pure squalane.

In early 2013, the company that developed a biotechnology process[20] (Amyris) for this started to produce microbial-derived sugar cane phytosqualane at its first industrial facility in Brazil. Trade named Neossance, the new phytosqualane has the potential to replace olive oil squalane since one hectare of a sugar cane plantation can produce up to 2.5 tons of squalane vs 50 kg of squalane obtained from a similar land extension planted with olive trees. Other companies such as Nucelis utilize glycerol in place of saccharose as raw material to produce squalene/squalane in a similar fermentation processes over genetically modified yeast.[21]

■ CATALYTIC HYDROGENATION

The highly exothermic hydrogenation of squalene is conducted in a stirred reactor of the size typically used in the fine chemicals industry, ensuring isothermic conditions.[22] The efficiency of hydrogenation equipment as measured by the volumetric mass transfer coefficient, indeed, rapidly diminishes with the scale of the reactor.[23] In detail, the reactors used may have either 1000 USG (3785 L) or 2000 USG, depending on the demand.

The reaction is a typical example of an heterogeneously catalyzed catalytic hydrogenation in liquid phase in which the metal nanoparticles (MNPs) that are present in the most frequenly used commercial catalysts are located at the external surface of the support ("eggshell" catalyst in Figure 3, whereas

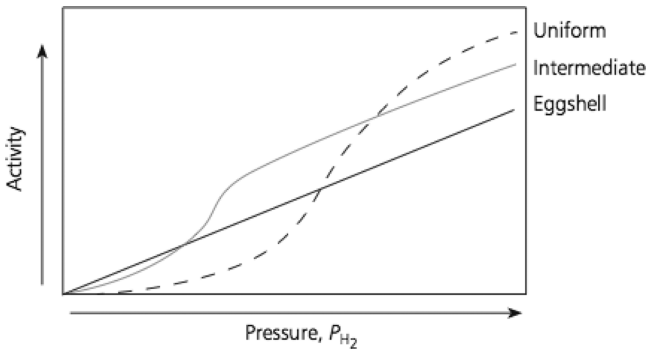

Figure 3. Influence of hydrogen pressure on the hydrogenation rate for eggshell, intermediate, and uniform catalysts. Reprinted with permission from ref 23. Copyright 2012 Johnson Matthey.

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for the "uniform" catalyst, MNPs are located in the inner porosity of the support).[24] The first catalyst employed to hydrogenate squalene was unsupported Raney nickel, the high surface area nickel catalyst from which aluminum is chemically removed by dissolving the aluminum out of Ni–Al alloy with NaOH.[25]

Today, a typical hydrogenation process carried out in industry makes use of 0.05 wt % nickel-kieselguhr catalyst at under 4 bar of H_2 pressure and 200 °C.[26] No solvent is employed, and, if the squalene is from skark liver oil, the reaction is complete after 3 to 4 h. Yet, if the squalene originates from olive oil, the inevitable presence of residual waxes requires harsher conditions and further purification.[27] Squalene is first winterized to precipitate the wax. Then, hydrogenation is carried out in two stages: a first step under 5 bar of H_2 pressure lasting 3 to 4 h, followed by a subsequent step at considerably higher pressure (30 bar H_2) to afford complete saturation. When the reaction is complete, the crude reaction product is filtered through silica gel, eluted with organic solvent (for example, EtOAc in hexane), and eventually further distilled after removal of the solvent.

During reaction over Ni-based Pt catalysts, extensive bond migration and dehydrogenation of squalene takes place.[28] Yet, because saturation of the double bonds is sought, low cost nickel catalysts remain the most widely used in commercial operations, as is common in the food industry,[29] even though extensive purification is required to remove most of the Ni leached into the squalane product to meet the maximum acceptable levels of toxic nickel compounds (Ni^{2+} and Ni^0) in a cosmetic product (0.2 ppm, even though out of 49 makeup cosmetic product commercialized in Canada, all were found to be positive for nickel, with an average content of 25.1 ppm; Table 2).[30]

Table 2. Heavy Metals of Concern Found in 49 of 49 Makeup Cosmetic Products Commercialized in Canada[a]

heavy metal	maximum (μg/g)	average (μg/g)	% of items
arsenic	70	1.8	20
cadmium	30	0.3	51
lead	110	4.6	96
mercury	0	0	0
nickel	230	25.1	100
beryllium	8	0.8	90
thallium	2.2	0.2	61
selenium	40	1.48	14

[a]Reprinted with permission from ref 30. Copyright 2011 Environmental Defence.

In practice, most industrial processes use distillation and chromatography to purify the crude squalane, to remove residual colored and odorant species, and to get rid of nickel. Depending on the purification process and the Ni catalyst used, out of the many available Ni-based hydrogenation catalysts, Ni-scavenging chromatographic silicas are used to remove Ni and decrease its concentration in the squalane oil to acceptable levels.

The other hydrogenation catalyst employed on an industrial scale is 5% Pd on charcoal (dry powder, 0.1 mol % loading). The reaction is carried out in a steel autoclave at about 160 °C under 150 bar H_2 pressure. When hydrogen uptake has ceased (typically, 16 h), the reactor is cooled, depressurized, and purged with nitrogen. The catalyst is filtered off. The crude product is purified by distillation in two stages, affording a distillate with a squalane purity of about 92–93%.[17]

A large number of supported Pd(0) catalysts for heterogeneous C=C hydrogenation reactions have been developed and are commercially available, including Pd/C, $Pd/CaCO_3$, and Pd/Al_2O_3.[31] However, such surface-derivatized catalysts, which are normally used for the synthesis of vitamins and other highly functionalized fine chemicals,[32] rapidly degrade further, adding to the cost of the product. When the catalyst loses more than its 50% of its initial activity, the spent catalyst is sent back to the manufacturer for refining and remanufacturing, allowing the intrinsic value of the metal to be recovered (even though a 2–5% Pd metal loss during refining is inevitable).[23]

Clearly, there is a need for better hydrogenation catalysts to convert squalene into squalane at lower pressure and temperature, especially now that vegetable squalene is poised to replace squalene of animal origin entirely.

FROM SUPPORTED TO ENCAPSULATED NANOCATALYSTS

Catalytically active metal nanoparticles (MNPs) supported on an inert, large surface area material, such as carbon, alumina, or inorganic salts, allow better and easier separation from the reaction medium as well as more effective use of the metal surface. Yet, supported MNPs are amenable to fast sintering and loss of catalytic activity.

Considerable (and at least partially successful) nanochemistry research efforts have been devoted to developing sinter-proof hydrogenation catalysts using, for example, preprepared colloidal MNPs with tuned size, shape, and composition that are then embedded into porous support shells.[33] Not only are the metal nanoparticles stabilized against particle conglomeration but also the selectivity in these uniform 3D catalysts is generally higher compared to that of surface (2D) derivatized catalytic materials.

The validity of this approach has been shown, for example, by comparing the catalytic performance of Pd particles deposited on the outer surface silica (Pd/SiO_2) with that of Pd MNPs encapsulated within the silica inner porosity ($Pd@SiO_2$).[34]

In this context, we have recently reported that the Silia*Cat* Pd(0) catalyst composed of Pd nanocrystals encapsulated within the sol–gel cages of mesoporous organosilica xerogel, first described in 2011,[35] is a highly active, chemoselective, and reusable catalyst (Figure 4) for the hydrogenation of squalene[36] under remarkably mild conditions, namely, 1 atm hydrogen pressure at 30 °C (or at 50 °C when shorter reaction times are needed) using an ultralow amount of catalyst (0.5–1.0 mol %). The extent of hydrogenation crucially depends on the purity of squalene.

If squalene oil of olive origin with a typical lower (82%) purity is used, the complete conversion requires the use of a lower (35%) flask volume capacity in order to increase the gas/liquid surface and to enhance hydrogen dissolution in the ethanol solution.

The large mesoporosity of these materials allows pore diffusion limitations that are observed with conventional uniform catalysts to be overcome while providing unprecedented selectivity in hydrogenation reactions as important as the stereochemically selective hydrogenation of vegetable oils, avoiding formation of *trans*-hydrogenated fats.[37]

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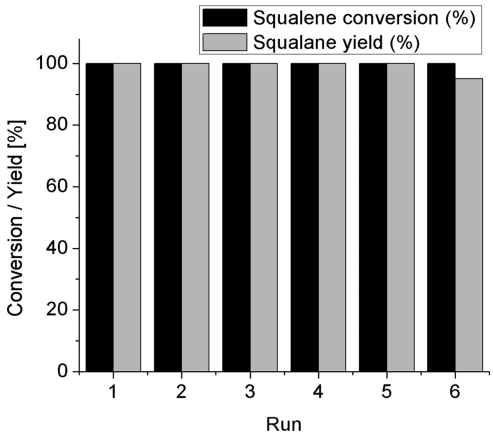

Figure 4. Reusability of the Silia*Cat* Pd(0) catalyst in squalene hydrogenation. Reprinted with permission from ref 36. Copyright 2014 Wiley-VCH.

■ CONCLUSIONS

Squalane is an exceptional emollient whose market in the past decade has decreased from 7500 to 2500 tons due to the non-sustainable sourcing of its precursor, the triterpene squalene obtained from shark liver oil or from olive oil distillates. Following the recent introduction of new biotechnology commercial processes based on fermentation of sugars (saccharose or glycerol) over genetically modified yeast, this situation will rapidly change. If these new biotechnology manufacturers are able to face the high and sustained demand for squalane, then a rapid increase in the market size is expected.

The high cost of squalane, however, is also due to the relatively high cost of current hydrogenation processes carried out in an autoclave at high hydrogen pressure and temperature using conventional supported catalysts such as Ni-kieselguhr or Pd/C. Hydrogenation of olive oil squalene, for example, accounts for up to 40% of the overall production cost of phytosqualane.

According to Tran and co-workers,[38] "very little work" has been reported on catalyst development for terpene hydrogenation. Recently, a new palladium catalyst based on Pd nanoparticles sol–gel encapsulated in a hydrophobized silica matrix was shown to be capable of fully hydrogenating squalene at room temperature under 1 bar H_2 pressure (hydrogen balloon). The catalyst is remarkably stable, showing once again the potential of basic nanochemistry research to solve practical chemical problems. This review tells the story of the evolution of the squalene sourcing and full hydrogenation, and identifies opportunities for its further improvement.

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Notes

The authors declare no competing financial interest.

Biographies

Rosaria Ciriminna is a research chemist at the Palermo Institute of Nanostructured Materials of Italy's CNR. Encompassing a broad field of activities in green, nano, and solar chemistry, her research, published in over 120 research papers, has been developed in cooperation with numerous laboratories worldwide. She mentors undergraduate and is member of doctoral committees abroad as well as of journal editorial boards.

Valerica Pandarus is a research chemist at SiliCycle, Inc. Following the completion of chemistry degrees at the Universities of Bucharest and Montreal, she is currently completing a Ph.D. with Prof. Serge Kaliaguine at the Université Laval. She has developed the Silia*Cat* S-Pd and Silia*Cat* DPP-Pd palladium(II) solid catalysts for cross-coupling reactions. Her contributions to the synthesis of silica-based catalysts for the green manufacturing of fine chemicals are reflected in >50 research papers and several patents.

François Béland is Vice President of R&D at SiliCycle, a leading manufacturer of functionalized silica gels for different applications in

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Mario Pagliaro is a chemistry and solar energy scholar based in Palermo, at Italy's Research Council. He coordinates Sicily's new solar energy and sustainable development regional research centre. Often cited for his excellence in teaching and writing, Mario has co-authored 19 books, 120 research papers, and several book chapters. His research, carried out in co-operation with researchers of 11 countries, has been translated into numerous new products. Since 2011, he chairs the FineCat Symposium on Catalysis for Fine Chemicals and the SuNEC Sun New Energy Conference, both held annually in Sicily.

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■ DEDICATION

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■ REFERENCES

(1) Sabetay, S. Perhydrosqualene. *Rev. Fr. Corps Gras* **1956**, *3*, 26−30.
(2) Tsujimoto, M. A highly unsaturated hydrocarbon in shark liver oil. *Ind. Eng. Chem.* **1916**, *8*, 889−896.
(3) Kim, S. K.; Karadeniz, F. Biological importance and applications of squalene and squalane. *Adv. Food Nutr. Res.* **2012**, *65*, 223−233.
(4) Huang, Z. R.; Lin, Y.-K.; Fang, J.-Y. Biological and pharmacological activities of squalene and related compounds: potential uses in cosmetic dermatology. *Molecules* **2009**, *14*, 540−554.
(5) Squalane; *Merck Index*, 14th ed.; Merck & Co. Inc: Whitehouse Station, NJ, 2012.
(6) The story of squalane in the cosmetic industry has been recounted recently by one of the industry's pioneers: Laserson, F. Neossance TM, un squalane de 3ème génération. *Expression Cosmétique* **2013**, 325−328.
(7) *Squalane (CAS 111-01-3) Market Research Report 2014*; Market Publishers: Limassol, Cyprus.
(8) The method relies on the $^{13}C/^{12}C$ ratio ($\delta\ ^{13}C$), which is significantly lower for vegetable squalene and squalane than for those of animal origin. See: Camin, F.; Bontempo, L.; Ziller, L.; Piangiolino, C.; Morchio, G. Stable isotope ratios of carbon and hydrogen to distinguish olive oil from shark squalene-squalane. *Rapid Commun. Mass Spectrom.* **2010**, *24*, 1810−1816.
(9) *Le prix hideux de la beauté: Le secteur cosmétique responsable de l'extinction de requins profonds*; BLOOM Association: Paris, 2012; http://www.bloomassociation.org/download/FR_Squalene_LONG.pdf (accessed, July 16, 2014).
(10) Mills, S. R. *2013 Credit Suisse Small & Mid Cap Conference Future of Energy Track*; Amyris Investor Presentation: September 18, 2013.
(11) Ramos, H.; Silva, E.; Gonçalves, L. *Reduction of deep-sea sharks' by-catches in the Portuguese long-line black scabbard fishery*, MARE/2011/06; Final Report to the European Commission: Brussels, 2013.
(12) Cockcroft, L. Cosmetics giants agree to stop using shark oil. *The Telegraph*, January 30, 2008.
(13) Auguet, C. A.; Casanovas, A. M.; Celades, R. A new source of squalane. *Drug Cosmet. Ind.* **1988**, *143*, 151−153.
(14) Tsimidou, M. Z. Squalene and tocopherols in olive oil: importance and methods of analysis. In *Olives and Olive Oil in Health and Disease Prevention*; Preedy, V. R., Ross Watson, R., Eds.; Academic Press Life Sciences: San Diego, CA, 2010; pp 561−571.
(15) Yeomans, M. Squalane: what some suppliers may not be telling you.... http://www.cosmeticsdesign-europe.com/Formulation-Science/Squalane-What-some-suppliers-may-not-be-telling-you (accessed August 26, 2014).
(16) Patent US20120040396A1 (Amyris).
(17) McPhee, D.; Pin, A.; Kizer, L.; Perelman, L. Deriving renewable squalane from sugarcane. *Cosmet. Toiletries* **2014**, *129* (6), 20−26.
(18) Patent ES 2011259 (Hispano Quìmica).
(19) Patent JP-A Hei 09/176057 (Koyo Fine Chemicals).
(20) Patent US 20110287988A1 (Amyris).
(21) Patent US 8470568 (Nucelis).
(22) Ciriminna, R.; Pagliaro, M. Green chemistry in the fine chemicals and pharmaceutical industries. *Org. Process Res. Dev.* **2013**, *17*, 1479−1484.
(23) Nerozzi, F. Heterogeneous catalytic hydrogenation. *Platinum Met. Rev.* **2012**, *56*, 236−241.
(24) Roessler, F. Catalytic hydrogenation in the liquid phase. *Chimia* **2003**, *57*, 791−798.
(25) Smith, A. J.; Trimm, D. L. The preparation of skeletal catalysts. *Annu. Rev. Mater. Res.* **2005**, *35*, 127−142.
(26) Wu, C.-S.; Tsay, Y.-J.; Liou, H.-J. Studies on the content and hydrogenation condition of squalene from the liver oil of deep sea sharks. *Taipei. J. Fish. Soc.* **1980**, *7*, 43−55.
(27) Watts, R. Personal correpondence with M.P. (August 2014).
(28) Dale, J.; Årtun, T. Double bond migration and dehydrogenation of squalene on hydrogenation catalysts. *Acta Chem. Scand.* **1956**, *10*, 439−444.
(29) Rajah, K. K., Fat products using fractionation and hydrogenation. In *Fats in Food Products*; Moran, D. P. J.; Rajah, K. K., Eds.; Springer Science & Business Media: New York, 1994; pp 277−317.
(30) *Heavy Metal Hazard: The Health Risks of Hidden Heavy Metals in Face Makeup*; Environmental Defence: Toronto, Ontario, Canada, 2011.
(31) See, for instance: *The Catalyst Technical Handbook*; Johnson Matthey, 2005; p 24.
(32) Bonrath, W.; Medlock, J.; Schütz, J.; Wüstenberg, B.; Netscher, T. Hydrogenation in the vitamins and fine chemicals industry—an overview. In *Hydrogenation*; Karamé, I., Ed.; InTech Open: Rijeka, Croatia, 2012.
(33) Jia, C. J.; Schüth, F. Colloidal metal nanoparticles as a component of designed catalyst. *Phys. Chem. Chem. Phys.* **2011**, *13*, 2457−2487.
(34) Forman, A. J.; Park, J. N.; Tang, W.; Hu, W.; Stucky, G. D.; McFarland, E. W. Silica-encapsulated Pd nanoparticles as a regenerable and sintering-resistant catalyst. *ChemCatChem.* **2010**, *2*, 1318−1324.
(35) Pagliaro, M.; Pandarus, V.; Béland, F.; Ciriminna, R.; Palmisano, G.; Demma Carà, P. A new class of heterogeneous Pd catalysts for synthetic organic chemistry. *Catal. Sci. Technol.* **2011**, *1*, 736−739.

(36) Pandarus, V.; Ciriminna, R.; Béland, F.; Pagliaro, M. Heterogeneously catalyzed hydrogenation of squalene under mild conditions. *ChemCatChem.* **2014**, DOI: 10.1002/cctc.201402668.
(37) Pandarus, V.; Gingras, G.; Béland, F.; Ciriminna, R.; Pagliaro, M. Selective hydrogenation of vegetable oils over silia*Cat* Pd(0). *Org. Process Res. Dev.* **2012**, *16*, 1307−1311.
(38) Garciano, L. O., II; Tran, N. H.; Kamali Kannangara, G. S.; Milev, A. S.; Wilson, M. A.; Volk, H. Development of Raney cobalt catalysts for the hydrogenation of squalene type compounds. *React. Kinet., Mech. Catal.* **2013**, *108*, 127−138.