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REVIEW

CHEMISTRY & BIODIVERSITY

Extraction of Natural Fragrance Ingredients: History Overview and Future Trends

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This work is dedicated to *Patrick Pellerin*, who was recognized worldwide as an expert in the field of extraction of natural products, and who taught us all a lot in this wonderful field.

For centuries, perfumes consisted in a combination of natural ingredients, mainly of plant origin. From the 19th century on, the advent of organic synthesis enabled the deployment of multiple synthetic olfactory notes, enriching significantly the perfumers' portfolio. Chemistry is ever since the foundation of modern perfumery. However, sustainable-minded consumers, massively rejecting synthetics for safety and ecological issues, engaged a global return to nature in numerous sectors, and the fragrance industry is not outdone. Sustainable extraction of natural products, making use of innovative technologies, process intensification and agro-based solvents, constitutes the answer to develop eco-conceived fragrant ingredients covering every olfactory family without endangering biodiversity any further. The objective of this review is to draw a clear picture of where those technological advances are today and to assess the ones that may be effectively transposed at the industrial scale tomorrow.

Keywords: fragrances, eco-extraction, alternative solvents, innovative process, natural products.

1. Introduction

Even if odors and the sense of smell remained mysteries for centuries, the link between humans and scent was always direct, sensorial and emotional.[1] The use of perfume in human culture has a very long history. Traces of scented substances used to make oneself more attractive, to mask unpleasant and offensive odors, or to make offering to gods, have been recorded in almost all ancient civilizations, for example Egyptian, Persian, Greek, Arab and Roman civilizations.[2]

In fact, for centuries, perfumes took two predominant forms: scents were used for ritual fumigations in censers or incense burners, as well as for body adornment. Hence, on one hand, perfumes' burning was widely practiced to please the gods during ceremonies, and to mask the smell of sacrificial offerings. The term *perfume* actually stems from the Latin locution *per fumum* meaning 'through smoke' and referring to the fumes of resins, gums, wood, spices and aromatic herbs burned during religious rites.[2] In ancient Egypt, incense was often referred to as the 'fragrance of the gods'.[3] On the other hand Egyptians mastered the techniques for capturing fragrances in fatty corpses (fats and oils), that is, cold maceration and hot decoction. Mainly dedicated to the elite, male and female alike, those unguents, or greasy ointments were smeared on the body for aesthetic and hedonistic purposes as part of the everyday life.[4] Those ancient perfumes were largely solid.

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The perfumer's art then spread throughout the antique world to Greece, Rome and the Islamic world, occupying a prominent position at the crossroads of the sacred, therapeutic and cosmetic.[4] The spread of Christianity and fall of the Roman Empire (5th century AD) led to a decline in the use of perfumes. Nevertheless, the tradition of perfume was kept alive throughout the Dark Ages, and the development of distillation techniques together with the deployment of international trade during the Middle Ages helped trigger its revival.[4]

Geber (Latinized version of his actual name Jābir ibn Hayyan, ca. 721–815), an alchemist from the early Islamic period, was actually credited with the development of several chemical laboratory apparatus, notably the alembic and retort, and with the description of many chemical processes including various forms of alchemical 'distillation'.[5,6] Later on, Avicenna (Latinized version of his actual name Ibn Sina, c. 980–1037), a Persian polymath, invented the condenser and distilled ethanol for the first time.[6]

The origin of extraction or distillation of essential oil is nevertheless associated to their collection after

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decantation using the Florentine flask invented by Giovanni Battista della Porta (1535–1615), a Neapolitan polymath, and described in his 'De Destillatione libri IX' written ca. 1563.[6,7]

The use of alcohol in the production of perfumes spread from the 16th century on.[4,8] A revolutionary advance in this sector was the invention by Gian Paolo Feminis of *Aqua Mirabilis*, a light and aromatic, 95% alcohol-based product imbued with notes of bergamot, lemon, orange, neroli, etc., considered both as perfume and medicine (used in a multitude of different ways: diluted in bath water, eaten on a sugar lump, as a mouthwash, as a tonic etc.).[9] Finally settling its production in the city of Cologne, Germany, Feminis transmitted the secrets of *Aqua Mirabilis* before his death to his grand-nephew Giovani Maria Farina (1685 – 1766) who perpetuate the tradition and began to spread this blend of essential oils and alcohol renamed *Eau de Cologne*, throughout Europe. From this period on, the usage of essential oils to manufacture perfumes democratized. In 1810, Napoleon Bonaparte ordained by decree that a distinction has to be made between pharmaceuticals and perfumes, and *Eaux de Cologne* were no longer drunk.[9]

Over these centuries, perfumes consisted in natural ingredients, essentially plant-based ones, but animal extracts derived from musk, whales or beaver were also used, and the perfumer's palette of fragrances was therefore limited. As thousands of kilos of plant material may be necessary to obtain just one kilo of essential oil, perfumes were particularly pricey and were consequently only available to some elite.

From the mid-19th century on, however, the advent of modern synthetic chemistry enabled the rapid deployment of multiple synthetic olfactory notes, enriching significantly the perfumers' portfolio and allowing greater creative freedom, hence democratizing fragrance: initially artisanal, perfumery grew rapidly into a powerful industrial sector.[9] Chemistry has ever since been the foundation of modern perfumery: synthetic fragrances, that is, fragrances that contain natural components in combination with synthetics, or that are totally made up from synthetics, are generally perceived as being stronger, longer lasting, more sophisticated and cheaper than natural fragrances.[10] Laboratory reproduction of natural fragrances presents multiple advantages, mainly economic and ecologic ones.[11] To synthesize molecules starting from inexpensive petroleum derivatives is indeed generally cheaper than to source, extract and purify from natural raw materials, and is also more reproducible from lot to lot.[10] In fact, the quality and cost of raw materials used in perfumes are highly vulnerable to changes in agricultural practices, social matters and politics, natural disasters, climate (sunlight, rainfall, temperature), soil and disease. Supply of some raw material is far from regular from one year to another, especially when it comes from one single geographical source. Synthetics constitute furthermore alternatives to ingredients sourced from fragile or depleting eco-systems and saved several plant and animal species threat from extinction due to over exploitation. Taking pressure off natural ingredient markets, it preserved user industries (for example fragrance and personal care companies) from severe shortages of certain raw materials ; one of the most compelling examples being the story of the sandalwood (*Santalum album* L.) industry.[12] In fact, for decades, the large majority of global sandalwood came from India, and most of it resulted from uncontrolled and fraudulent harvesting. Sandalwood's importance in numerous sectors (used for its sweet, warm, spicy and tenacious fragrance in perfumes and personal care, as well as in woodworking, worshiping in Hindu and Buddhist rituals, traditional medicine, etc.) consequently induced its irrational overexploitation leading to global shortage and massive increase of market price of sandalwood.[13] As a consequence, *S. album* was inscribed on the IUCN (International Union for Conservation of Nature) red list as a vulnerable species in 1997, and its exploitation is strictly under control ever since.[12] Lots of effort have been put in the search for synthetic substitutes for sandalwood: the synthesis of santalol revealing itself so costly, it is of no interest for the perfume industry, and pushed forward the development of chemicals with a sandalwood-typical note.[14]

Among the emblematic synthetic aromatic compounds developed in the 19th century, one can cite benzyl acetate (1855), still used nowadays for its jasmine notes, and the vanilla substitutes, for example coumarin (1868) and vanillin (1874).[15,16] This latter synthesis is often considered the turning point in modern perfumery:[17] today, both synthetic and natural ingredients are mixed up in perfumes which are often quite complex.

As it cannot be patented, with the advance of modern analytical techniques, a perfume formulation can easily be analyzed and copied if only composed of commercially available raw materials. The need to be unique and different is driving the perfume industry to circumvent this problem: new odorants can be patented, and if the company that produced it decides to retain this patented odorant as a *captive* (or *captive* *odorant*) only for its exclusive use rather than to sell it, it drives differentiation in formulations that remain inimitable as long as the patent is valid.[9,18] To provide newness and innovation to the perfumers' palettes, *captives* must display a specific scent to provide a signature effect on a fragrance and should be unobtainable using other raw materials. When the patent is close to expire, the *captive* is generally released on the market; examples of such commercially-released *captives* include Hedione and Moxalone, which were once the respective signatures of *Eau Sauvage* by Dior, and of *CK Be* by Calvin Klein.[19]

With hundreds of new fragrances brought to the market every year worldwide, the consumers' choice is large, and manufacturers are seeking innovation to stand out from competitors in this billion-dollar industry.[20,21] Innovation in the sector may come through innovative perfume ingredients: key players in the market are focusing on developing eco-conceived natural fragrance ingredients, primarily due to the rising concerns of sustainable-minded consumers regarding synthetic molecules and their related safety and ecological issues.[22] Together with agro-management and sustainable raw material production, green extraction methods, and more particularly the use of new solvents and/or of activation techniques to replace or supplement conventional heating, may constitute crucial breakthroughs to fully address this triple challenge of allying innovation, technology and sustainability to develop a spectrum of fragrances covering every olfactory family, while satisfying people's emotional needs.

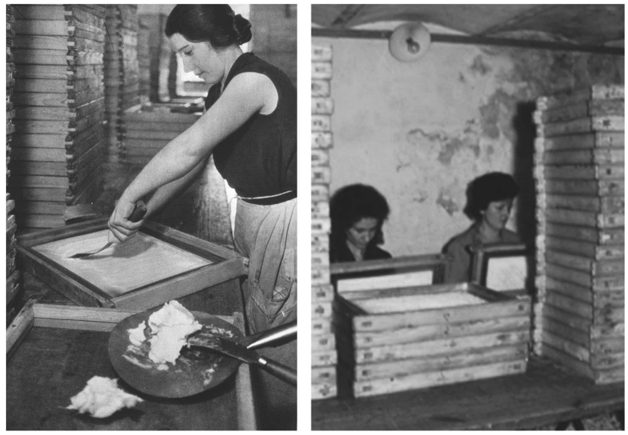

Figure 1. *Enfleurage* process.

2. Conventional Techniques

The crucial step to make natural perfume ingredients consists in the extraction of the fragrance from plants. Extraction was used throughout the human history: Phoenicians, Arabs, Indians, Aztecs, etc. possessed innovative extraction processes and natural products have probably been extracted since the discovery of fire for food, medicines, perfumes, etc.[23]

2.1. *Oil Extraction and* Enfleurage

Capturing fragrances into fatty corpses, through extraction techniques such as cold maceration, or hot decoction, has been performed in perfumery since ancient times: Egyptians and Romans did already use oils (for example olive oil principally) to extract fragrances. Although very popular, the resulting products (perfumes and pomades) did not display the olfactory power of our modern perfumes.[4]

The *enfleurage* process consists in trapping the fragrant compounds of fresh flowers in odorless fatty corpses, as they possess a high absorption power (*Figure 1*). *Enfleurage* was performed as follows: fresh petals or whole flowers were pressed in the layer of fat smeared on sheets of glass and mounted into large rectangular wooden frame that could be pilled. The petals/flowers were allowed to set for days or weeks depending on the species, so the scented molecules infused the fat. The depleted petals are then repeatedly replaced by fresh ones for up to months until the fat reaches the desired saturation.[24] *Enfleurage* was appropriate for delicate flowers such as jasmine, narcissus, jonquil, tuberose, etc.[24] Vegetal oils and animal fats (usually lard or tallow, from pork or beef, respectively) were preferentially used after deodorization to practice enfleurage, but some perfumers were also quite keen to incorporate in their formulation fragrant ingredients presenting the *sui generis* odor (Latin locution meaning 'of its own kind') of these fatty corpses.[24]

The hot maceration process enables the reduction of extraction time: petals are directly immersed in molten fat maintained at a medium temperature (ca. 45–60 °C to impair solidification) for 1 to 2 h, depending on the plant species (hot maceration is appropriate for rose, carnation, hyacinth, etc., but not for more delicate flowers).[24] After each immersion, the fat is filtered, and fresh petals are treated, and after several immersions, petal wastes, and water are removed.

In both instances, the resulting product is a pomade, that could either be used as it was, or could be further washed with alcohol to obtain an absolute.[24]

Enfleurage was developed at industrial level in southern France in the 19th century to produce flower concentrates.[25] However, both *enfleurage* and hot maceration are virtually obsolete nowadays, for several reasons including the fact that by today's standards, they are tedious, labor-intensive, time-consuming, and quite expensive methods.[8,26] Furthermore, the sensual experience conveyed by the resulting products, that is, the 'greasy touch' and the 'fatty odor' do not meet modern trend of lightness governing the fragrance industry.[27] Finally, although products of animal origin are not prohibited in the perfumery world, their utilization felt progressively into disuse, a fact that did not favor the survival of such techniques.

Figure 2. Conventional hydrodistillation of rosemary essential oil in Tunisia (picture: X. Fernandez).

2.2. *Essential Oils*

The perfume manufacture was made viable through the development of distillation techniques by the Arabs, the spread of the still and the translation of alchemy treaties by doctors from the School of Salerno in the 12th and 13th centuries.[4] Although distillation techniques were improved, the production of essential oils remained essentially unchanged for centuries, but was industrialized during the first half of the 19th century as a consequence of the pressing demand for these oils as perfume ingredients.[25]

The International Organization for Standardization (ISO) defines an essential oil as a 'product obtained from a natural raw material of plant origin, by steam distillation, by mechanical processes from the epicarp of citrus fruits, or by dry distillation, after separation of the aqueous phase – if any – by physical processes'.[28] Essential oil may be obtained from a variety of plant parts (flowers, leaves, roots, bark, seeds, peels, etc.).

2.2.1. *Hydrodistillation*

Due to its simplicity, hydrodistillation is the most popular and cost-effective method used today world widely to produce the vast majority of essential oils at a reasonable price in less developed countries. Hydrodistillation apparatus come in a variety of capacity and complexity, ranging from the simplest systems heated by direct firing (*Figure 2*) to modern units that are totally regulated for full control of operational parameters (steam flow regulation, temperature, pressure, etc.) and gently and uniformly heated through the circulation of steam in the still's double bottom. Low-cost and easy-to-operate field distillation units are extremely popular with essential oil producers in developing countries. Mobile units can even be brought directly to the fields; such devices with enlarged field of application, avoid transportation of fresh plant material over long distances, and hence limit the potential alteration/loss of odorants of this raw material through fermentation notably.[8]

The plant material is packed in boiling water in a still and releases essential oil which is then driven by the steam by azeotropic distillation (*Figure 3*). Once those vapors consisting in a mixture of water and oil, have been condensed by indirect cooling with water, the essential oil easily separates from the water and can be collected. The recondensed water is referred to as hydrosol, as hydrolate, or more rarely as herbal distillate; when flowers are used as starting material,

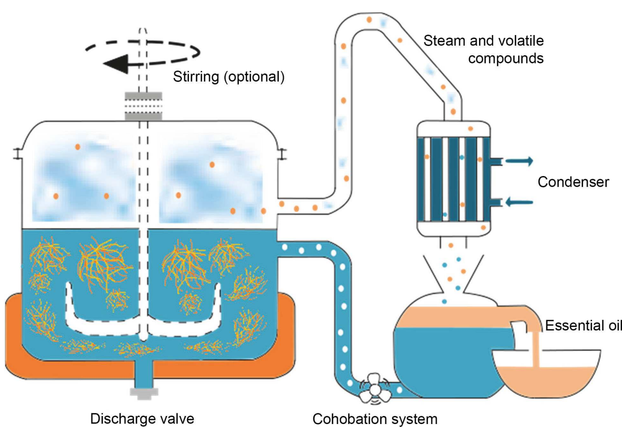

Figure 3. Hydrodistillation of essential oils (modified from [29]).

this recondensed water is specifically referred to as flower water.

Cohobation is a procedure that enables the distilled water to return to the still after the oil has been separated from it, so that water, that is, the steam source, never runs out. The principal behind this kind of circulation process is to minimize the losses of oxygenated constituents which dissolve to some extent in the condensate water.

Hydrodistillation constitutes an efficient extraction process, that is nevertheless highly energy-consuming due to the necessity to heat the still and to cool down the vapors generated.[30,31] If heating is not properly controlled, distillation yield may vary from one batch to another. Furthermore, in some modest apparatus, there is a likelihood of plant material being in direct contact with the heating source at the bottom of the still, hence getting charred and thus imparting an objectionable odor to the essential oil. Similarly, the hydrodistillation process being a long process that could last for several hours, prolonged contact between the plant material and boiling water can cause unwanted thermo-decomposition of the constituents of the essential oil and bring subsequent off-notes to the end-product, the quality of which is hence diminished.[24,32]

Turbodistillation constitutes a greener alternative to hydrodistillation, particularly suitable for hard-to-extract and coarse raw materials (spices, woods): combined effect of stirring, snipping and physical destructuration of plant material enables considerable reduction of distillation times, hence a reduced energy consumption.[8,33]

2.2.2. *Steam Distillation*

The problem of off-notes can be overcome thanks to dry/direct steam distillation: the steam is generated in a separate vessel and brought in contact with the plant material through a perforated inlet (the steam coil) to vaporize the plant's volatile molecules (*Figure 4*).[24] Those compounds then circulate to the condensation flask (also known as the condenser), where the vapor cools back into liquid form, and as for hydrodistillation, static separation of floral water/hydrosol from the essential oil occurs.

Steam in classic distillation units is at atmospheric pressure and hence reaches a maximum temperature of 100 °C; but modern steam distillation units can be operated under high pressure, and correspondingly higher temperature, hence enabling much more rapid and complete distillation of essential oils.

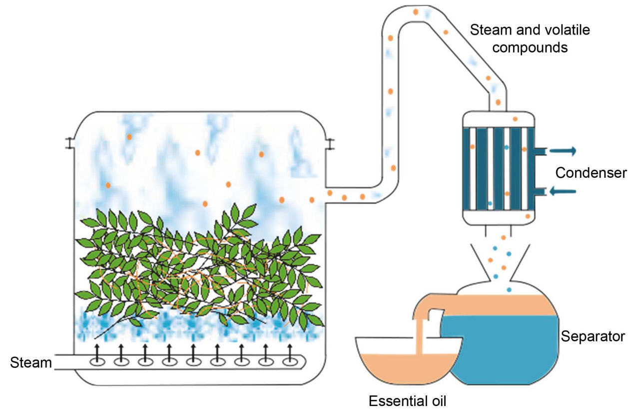

Figure 4. Direct steam distillation of essential oils (modified from [29]).

The quality of the essential oil obtained by steam distillation usually exceeds the one of essential oil obtained by hydrodistillation. Steam distillation is energy-efficient compared to hydrodistillation to higher thermal efficiency.

2.2.3. *Expression*

Expression is an extraction method specific to *Citrus* species (orange, bergamot, grapefruit, lemon, etc.) to obtain the essential oils. Also referred to as 'cold pressing' as it does not require a heating source, hence preserving the intact olfactory quality of the end-product, expression involves a physical crushing of the essential oil glands located in the fruit rind, or in the outermost waxy layer of the fruit's peel to release the oil.

In the past, expression was performed by hand, through the 'sponge pressing' method: after abrasion or incision, *Citrus* rind or zest was soaked in warm water to make the fruit parts more 'receptive' to the subsequent extracting procedure. A sponge was then be used to squeeze those fruit parts and to directly absorb the essential oil which was then easily collected in a container simply by pressing the sponge over it and by leaving the liquid stand a bit to allow the separation of the essential oil from the water/juice.[24,34]

Being an extremely slow process, hand pressing is obviously impractical and, over the years several machines have been designed and improved to either press the peel or the whole fruit and then separate the oil from the juice (*Figure 5*).

The *Ecuelle* process, particularly used in Italy, is one of the oldest methods of extraction, that involves

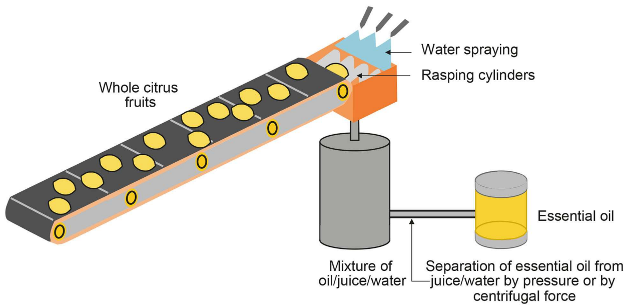

Figure 5. Expression of the whole citrus fruit to obtain essential oil (modified from [36]).

puncturing of fruit rind by metal needles just long enough to penetrate the fruit epidermis while the entire device is rotating; the released essential oil is then collected in a container and left to decant.[24]

Modern semi-industrial techniques are based on the same basic principles as those of either the old-fashioned sponge method or the *Ecuelle* process.[35]

The *sfumatrice* functions as the sponge method: the peels of the de-juiced fruits are driven into a rotating drum which rolls and presses them against the machine walls, causing the consequent break of the essential oil glands, and the subsequent release of their content. Sprayed water is used to collect the freed essential oil mixed up with aqueous material and solid fruit residues. The oozed essential oil is collected after filtration, centrifugation and decantation of this mixture.[8]

The *Ecuelle* principle has been applied to develop the *pelatrice* process in which the entire *Citrus* fruits are rotated against the abrasive shell by a slow-moving Archimedean screw leading the oil glands to burst and release their content. The oil-water mixture is sprayed away and passes through a separator to eliminate any solid particles; centrifugal separators are then used to separate the oil from the watery material.[37]

At the industrial scale, *Citrus* essential oils are obtained as a by-product of *Citrus* juice production. Fruits enter the extractor through a conveyor belt to be selected (regarding their form, firmness, etc.) and washed with water containing a detergent (sodium hypochlorite, etc.) to get rid of any exogeneous body (microorganism, etc.). After rinsing and brushing steps, the selected fruits enter the proper extraction unit, where the oil extraction can either precede (as in the *pelatrice* process), succeed (as in the *sfumatrice* process) or take place simultaneously with the juice extraction.[35] The FMC in-line extractor, from JBT FoodTech, constitutes a good illustration of this latter model: the extraction unit consists into upper and lower stainless steel cups, both equipped with cutters.[8,38] Once the whole fruit in place in the lower cup, the upper one moves downward to press the fruit, and therefore cut the top and bottom peels. The pressure maintained on the fruit pushes the resulting juice into a tube implemented into the lower cup, while the essential oil is driven away by sprayed water; essential oil is then separated from water by centrifugal force.[8] Expression provides high quality *Citrus* oils with characteristic fragrances very similar to the ones of fresh *Citrus* peels; they may contain small amounts of naturally occurring non-volatile residues such as waxes.

Citrus oils can also be distilled from either the peels or whole fruits; the fragrance of those distilled oils differs from those of the expressed ones. The distilled ones are notably devoid from non-volatile furocoumarins and are hence less photosensitizing.

2.2.4. *Pyrogenation*

Pyrogenation corresponds to a destructive distillation of the bark or the wood of some plant materials in the absence of air: a number of volatile compounds are freed, and the residual mass in the oven is charcoal. The resulting product, collected by gravity, usually separates into two phases, an aqueous one and an oily one which corresponds to tar characterized by an empyreumatic fragrance. This process was notably used for the extraction of black birch or cedar oils. This tar could sometimes be further steam distilled to produce woody essential oils.

This process is particularly used to produce rectified cade essential oil: cade oil obtained by destructive distillation of wood of *Juniperus oxycedrus* L. is potentially carcinogenic due to the presence of PAHs (Polycyclic Aromatic Hydrocarbons), mainly benzo[a]pyrene, and is further steam distilled to obtain rectified cade essential oil, which use is safer.[39]

2.2.5. *Conclusive Remarks*

Essential oils are used in the formulation of fragrance compositions: they contribute mainly to the top notes and fairly well to the body notes but fall short regarding the base notes. Furthermore, some raw materials may be too delicate to withstand the pressure and distress of distillation (for example heat can actually deteriorate the delicate jasmine petals); for such plant materials, as well as for resinous ones that yield low amounts of essential oil, solvent extraction is best suited.

2.3. *Solvent Extraction*

This method employs solvents (if the use of benzene has been prohibited several decades ago, toluene, hexane, heptane, petroleum ether, but also occasionally dichloromethane, ethanol, methanol, etc. are still employed) to isolate metabolites from plant materials, either fresh or dry.[8] Many parameters influence the quality of the resulting extract (*Figure 6*).

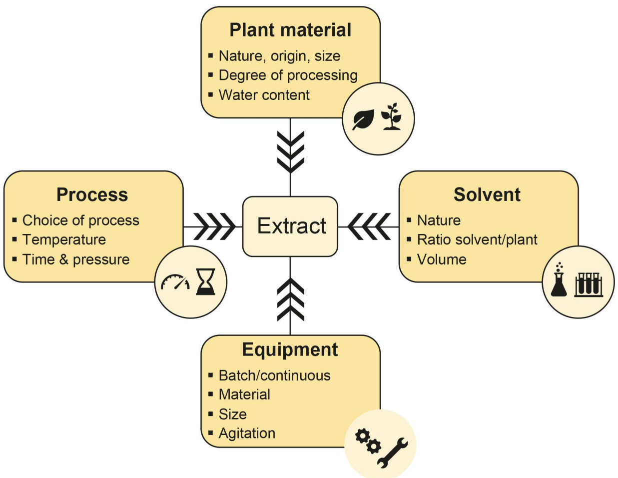

Figure 6. Parameters influencing extraction.

If one considers more specifically the perfume sector, the advantage of solvent extraction over distillation is the lower temperature used during the process, implying a reduced risk of molecules' modifications linked to high temperatures, as the solvent is usually used at room temperature.[26] However, regarding the extraction's difficulty and the plant's delicacy, hot solvent can also be used to increase the speed of the process.[8,26]

Fresh plants are mainly composed of water and generally only contain a very small fraction of fragrant molecules. Apolar solvents such as hexane or petroleum ether are key solvents used for the extraction of this fragrant fraction consisting mainly in low polar volatile compounds, and give rise to particular extracts, specific to the perfume sector, that is, concretes, resinoids, and absolutes (see *Sections 2.3.1* and *2.3.2*).[40] Solvent extraction, known since the 18th century, has only been industrial implemented at the very end of the 19th century.[8]

The plant material is placed into an extraction vat, and the solvent, gradually fed into the vat, seeps through it and dissolves the fragrant volatile compounds, together with non-volatile plant material such as waxes and pigments, that have to be removed at some point through the process.[8] The solvent charged with the dissolved compounds is then evaporated under partial vacuum to obtain a concrete or a resinoid, that is, a semi-solid waxy substance, containing both volatile and non-volatile molecules, some of which being insoluble in alcohol.[8,41]

Legislation requires the removal of noxious solvents to a prescribed maximum residual level varying according to the following application of the extract (food application, cosmetics, perfumes, etc.).[32] All those solvents are of concern due to the long term and serious effects that they may exert on human health, and are classified among the CMRs, that is, substances that are Carcinogenic, Mutagenic or Reprotoxic, that is, toxic to reproduction.[42,43]

2.3.1. *Concretes and Resinoïds*

Concretes are produced mainly from fresh materials such as flowers (rose, jasmine, mimosa, etc.; the extraction yields of flowers concretes are usually below 0.3 % (*w/w*)[40]), but other plant materials can also be extracted this way (clary sage, oak moss, etc.).[25]

Resinoids are odorant extracts obtained through the same process: they result from the extraction of dry or semi-dry plant material or plant exudates (balsams, gums, resins, oleoresins) and mainly consist of non-volatile, resinous compounds, and are usually highly viscous.[25]

Concretes and some resinoids are seldom used as such in perfumes because of their high fatty/waxy content (hydrocarbons, fatty acids, triglycerides, etc.) insoluble in ethanol, but rather constitute intermediates between the raw material and the absolute.[24]

2.3.2. *Absolutes*

Absolutes are a further derivation of concretes and resinoids: they are obtained by the alcoholic purification of a primary solvent extraction product, that is, concrete or resinoid. In fact, those later may be further dissolved in warm ethanol to produce absolutes: their heavier non-volatile components (mainly waxes) are only partially soluble in ethanol, and will precipitate while the mixture cools down, being then easily separated by filtration. The absolute corresponds to the thick liquid or the paste remaining after ethanol

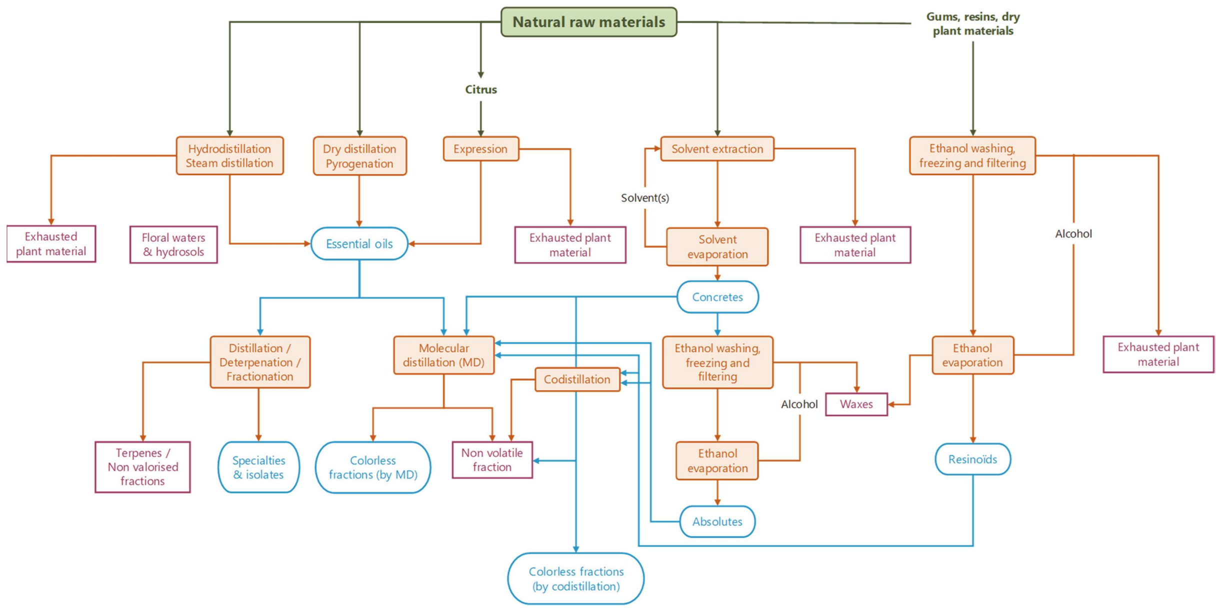

Figure 7. Conventional extraction techniques and resulting types of extracts.

elimination; it is the most concentrated form of fragrant material. Being totally soluble in ethanol, absolutes can be incorporated in alcohol-based perfumes.[25,41]

2.4. *Specialties*

Specialties are fractions obtained from essential oils or extracts by fractionation which enables a fine separation of molecules. Several technologies can lead to fractions or specialties, for example hydrodistillation, fractional distillation (generally vacuum distillation), molecular distillation, column chromatography, techniques based of the principle of liquid-liquid extraction such as washing, etc., see *Figure 7*. Those later (column chromatography and liquid-liquid extraction), being both time- and solvent-consuming, became rapidly obsolete.

Nowadays the techniques used intensively are:

- fractional distillation, a separation technique of a mixture into its individual component parts by heating them to a temperature at which one or more fractions of the compound will vaporize. Fractional distillation also referred to as fractionation, enables a fine separation of odorant molecules from essential oils, and the resultant fractions display slightly different odor qualities.[8,25] This technique is however not transposable to fractionate extracts.
- molecular distillation, which can be used to deodorize both essential oils and extracts, to remove colors or contaminants, etc., is based on the separation of the essential oil/extract into fractions based on differences in boiling point ranges. As the application of heat to the essential oil/extract is quite punctual and short, the odor of the essential oil/extract is not deeply modified but the unwanted molecules are removed.

An essential oil can be deterpenated (by several methods including distillation and liquid-liquid extraction) to specifically remove monoterpenoid hydrocarbons to leave only the oxygenated species and so increase the strength of its odor.[35,44,45]

3. Conventional Techniques: A Necessary Evolution?

Even if hydrodistillation and steam distillation can be perceived as green techniques, they are actually not sustainable due to their high water and energy consumption.

Similarly, solid-liquid extraction conventionally used to obtain natural extracts consists in several unitary operations, including the plant material pretreatment (drying, grinding, etc.), the raw material extraction itself and finally, the post-treatment of the resulting extract (filtration, concentration, etc.). All these single steps, and more particularly the extraction one, are often time- and energy-consuming, particularly when not optimized, and induce consumption of quantity of water and/or solvents while generating large amount of waste materials.[46] Furthermore, the resulting product may contain traces of residual petroleum based-solvents (potential or recognized CMR), contaminants from starting material, or denatured compounds due to drastic extraction conditions, etc., that may impair its safety and quality.[46]

In recent years, with the increasing environmental concern, consumers are profoundly changing their habits and are actively scrutinizing the quality of the products they use daily. They are much more ingredient-conscious and are seeking for naturality, transparency, traceability, eco-friendly sourcing and fair-trade practices across market categories. Consumers are particularly interested to know whether companies are using eco-compatible methods to produce the ingredients entering in the products they use daily. In this global quest for a sustainable and green future, perfumes are not outdone, and the topic of sustainability is currently one of the central concerns of the fragrance industry, which is required just as other industrial sectors to provide tangible solutions to mitigate its environmental footprint. In this context, innovation is mandatory to increase the extraction efficacy and to obtain safer extracts of higher quality while reducing the number of unitary operations, and subsequently reducing both the economic and ecological costs (energy and solvent consumption, waste generated; *Figure 8*).[46]

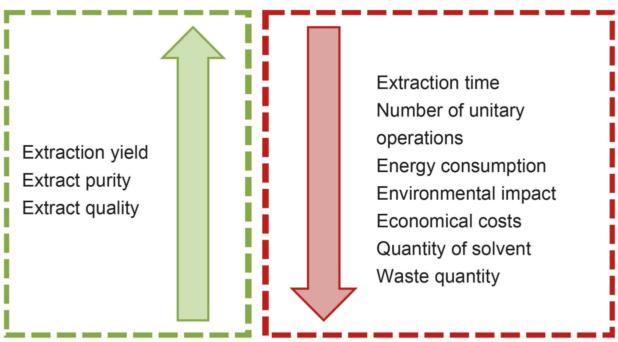

Figure 8. Direct effect of the use of intensification during extraction processes.[46]

4. Innovative Techniques for Green Extraction

The global shift of the fragrance industry towards natural products innovation, through the development of new olfactory notes, green extraction and transparency started in the early 1980s, fueled notably by the pressure exerted by certifying bodies to restrict or even prohibit petroleum-based solvents in plant extraction processes, for health, safety and ecological issues.[17] Such green movement is even more exacerbate by the urgent need to save energy and to use it more efficiently. Conventional solid-liquid extraction with fossil-based solvents such as hexane or petroleum ether turned consequently rapidly obsolete,[17] creating room for cleaner extraction technologies.

R&D activities on plant extraction had to evolve accordingly and technical improvements were necessary to lessen their negative environmental impact while still meeting the challenges faced by the fragrance industry. The extraction process being at this stage the limiting step for the renewal of the fragrance ingredients sector, developments and innovation became mandatory.

Several emerging technical improvements (developments in activation techniques, use of new alternative solvents) are helping to overcome the limitations imposed by conventional extraction techniques and new high-quality natural ingredients have consequently emerged to enlarge the perfumers' palette.[30]

4.1. *Green Extraction Principles and Opportunities*

Sometimes also called sustainable chemistry, green chemistry is a concept introduced at the beginning of the 1990's and properly defined by Anastas and Warner from the EPA (Environmental Protection Agency) in 1998. Often considered as the chemistry of the 20th century, green chemistry focuses on the environmental impact of chemistry through the optimization of the energetic consumption of processes, the recycling of both raw materials and by-products generated by chemical reactions, the waste reduction and the lowering of health and environmental impacts of such processes, and advocates to minimize or even eradicate the use and generation of hazardous substances.[23] In fact, even considered as 'clean' compared to other heavy chemical industries, the extraction of natural products using conventional techniques and solvents was not actually green as it means high energy and often very large amounts of solvents consumption, for an extraction yield usually quite low. The environment footprint of such a process is usually even further impacted using enormous quantities of water used as a cooling agent.

The challenges of the 21st century regarding environmental preservation and public health protection actually imply the need for disruption rather than continuity.[23] From the meeting of the well-known 12 principles of green chemistry[47] with the 12 principles of green engineering developed to make greener chemical processes or products[48,49] (*Supporting Information*), directly stems the concept of green extraction.

Constituting a step forward towards a sustainable valorization of the biodiversity, compatible with the environment preservation, the principles of green extraction (*Figure 9*) encourage the design of extraction processes allying a reduced energy consumption, and the use of alternative solvents and renewable natural products, to ensure the production of high quality-extracts that are safe both for operators and end-consumers and for the environment.[23,30] Those principles constitute rather guiding principles which implementation on a daily basis challenges the industries to be more ecologic, economic and innovative.[23]

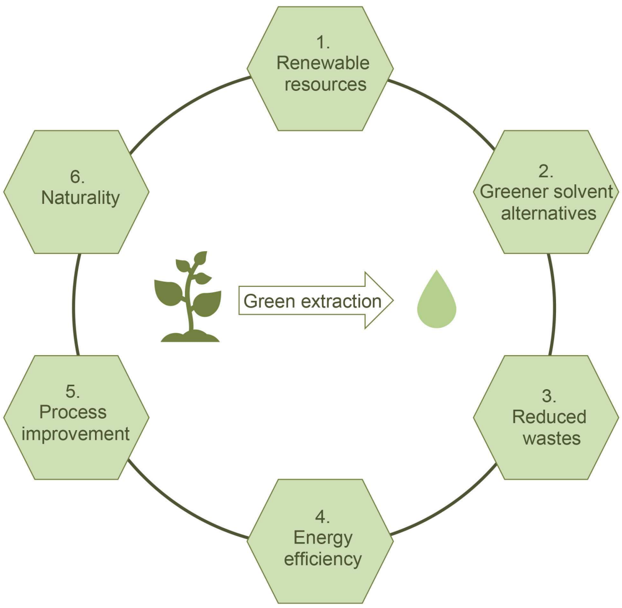

Figure 9. The six principles of green extraction.[23,30]

To avoid the overexploitation of natural resources, and ultimately, the extinction of endemic species, that may be inevitable in front of the increasing demand for natural extracts from the food-processing, pharmaceutic and cosmetic industries, the 1st principle naturally recommends the use of renewable raw materials. The implementation of this principle implies the exploitation of cultivated plants from controlled crops (well-reasoned inputs, newly domesticated species, that is, native plants identified in the wild as 'of interest' and placed under cultivation to avoid their rarefaction/extinction underpinned by their collection in nature, etc.). Varietal improvement may also be adopted to fit to this 1st principle: it consists in the hybridization of existing varieties selected for the respective qualities, to generate plants displaying modified phytochemical profiles, higher concentrations of active ingredients, better production yields, increased disease- and pest-resistance, and better adaptability to specific soil and climatic conditions.[23]

The efficiency of solid-liquid extraction is mainly conditioned by the nature of the solvent used: it should be selective, inert regarding the compounds to extract and volatile enough to be easily and safely removed at the end of the process. The 2nd principle recommends favoring green alternatives to conventional petroleum-based solvents, given the health and environmental issues linked to their usage. Apart from efficiency and selectivity, the ideal alternative should stem from renewable resources, be available at reasonable price, while being safe for both human health (non-CMR, non-allergenic and non-toxic) and environment (be recyclable and non-CO_2 emitting). Furthermore, the possibility to develop solvent-free processes should always be assessed in first instance.[23]

Industries extracting natural raw materials usually only produce one unique value-added product from one single biomass, hence leaving enormous quantities of highly environmentally impacting wastes (pulp, pomace, peels, etc.) behind. Urged to decrease their environmental impact and to provide concrete waste management solutions, industrials are taking concrete steps to identify new outlets development for their activities' by-products.[50] Properly managed, these wastes could become main streams of original raw material sources for other industrial sectors (biomaterials, human and animal nutrition products, etc.), as stated in the 3rd principle.

The 4th principle advocates a reduced energetic consumption for both cost-effectiveness and environmental issues. Ways to efficiently decrease this consumption include the optimization of existing processes, the recovery and reuse of the freed energy, the intensification of existing processes using innovative technologies (ultra-sound, microwave, pulsed electrified fields), or the development of innovative processes preferentially avoiding heating/cooling steps, that are particularly energy-consuming.[23]

The 5th principle recommends the reduction of unitary operations during extraction through notably the intensification of the whole process, and favor safe, robust and controlled procedures. Direct extraction of the raw material in the final solvent, that is, in the solvent used to formulate the extracted product for its final application, enables to avoid several tedious unitary operations (solvent elimination, reformulation of the extract in the appropriate solvent).[23]

The 6th principle advocates to place a premium on the naturality of the product generated, that should be free of denaturized molecules, biodegradable and free of contaminants (microorganisms, pesticides, heavy metals, etc.), while presenting a low environmental footprint (evaluated through a Life Cycle Assessment (LCA), consisting in multi-criteria study aiming at quantifying the potential impacts of a product during its whole life cycle, from production to disposal/recycling).[23,46]

Alternative innovative processes were progressively developed to satisfy to the following criteria: higher efficiency, reduced solvent consumption, automation easiness, lowered environmental and health impacts.[51] Applied on traditional raw materials, such innovative processes can generate new products, with their own fragrances and unusual qualities.[52]

4.2. *New Solvents*

Solvents represent approximately 80% of the total volume of chemicals entering most of the chemical processes.[53] Most solvents used daily in the fragrance sector are flammable, noxious and highly volatile, leading to the release of volatile organic compounds (VOCs) in the atmosphere. Current regulations (REACH – Registration, Evaluation, Authorization and Restriction of Chemicals – notably) become increasingly restrictive regarding those, and users of these solvents must demonstrate the safety of the resulting products in regards with solvent traces' content.[30] These considerations consequently fueled the search for novel and greener alternatives, if only for specific applications, to replace those conventional petroleum-sourced solvents. However, despite this, no regulation nor reference frame does exist to currently decide whether a solvent is green or not; some solvent selection guides have emerged here and there from specific sectors, and notably from the pharmaceutical industry, but they are not drawing unanimous conclusions regarding the greenness of individual solvents.[54,55]

Table 1. The 12 criteria a solvent must meet to be classified as green.[56]

1. Availability.
   Green solvents need to be available constantly on a large scale (production should not fluctuate greatly).
2. Price.
   Green solvents' prices should be both competitive and stable (not subjected to price's volatility).
3. Recyclability.
   Green solvents have to be fully recyclable, using preferentially eco-efficient procedures.
4. Grade.
   Technical grade solvents are preferred, as higher purity means the use of energy-consuming purification processes.
5. Synthesis.
   Green solvents should be obtained through energy-saving process.
6. Toxicity.
   Green solvents must display negligible toxicity both towards biodiversity and humans.
7. Biodegradability.
   Green solvents should be biodegradable and should not generate toxic metabolites.
8. Performance.
   Green solvents should be equally or even more performant than conventional ones in terms of viscosity, polarity, density, etc.
9. Stability.
   Green solvents should be thermally and electrochemically stable.
10. Flammability.
    Green solvents should not be flammable.
11. Storage.
    Green solvents should be easily stored and must fulfil regulation regarding safe transportation.
12. Renewability.
    Green solvents should be obtained preferentially from renewable raw material.

Hence, how can we define a green solvent? No clear definition exists nowadays[23] but, inspired by the twelve principles of green chemistry[47], Gu and Jérôme (2013) proposed twelve criteria to be met by a solvent to be qualified of 'green' (*Table 1*).[56]

However, in most of the cases, solvents do not meet all 12 criteria and these alternatives are considered as green if they are actually 'greener' than the conventional ones:[56,57] the ultimate choice consists in the best compromise between several requirements (*Figure 10*). The ideal way to study a solvent's sustainability is to perform its LCA as described in International Norms considering the materials and energies

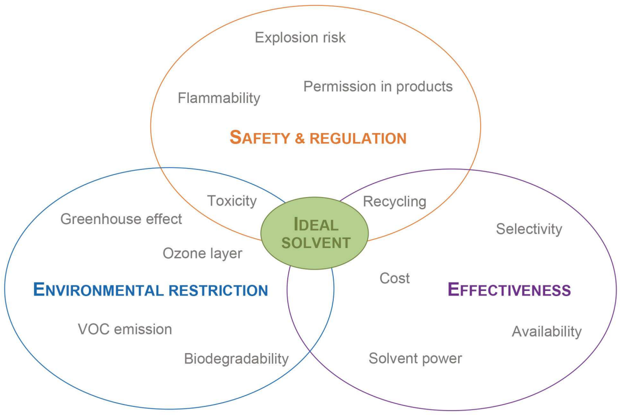

Figure 10. The ideal solvent is a good compromise between several criteria.

flows of every single step in its life (extraction, processing, transport, distribution, use, end-of-life, etc.).[46,58–60]

Recently, new regulations about consumer's safety have incited producers of natural extracts to look for safer and renewable extraction solvents; among those alternatives to fossil solvents, one can cite agro-based solvents including plant oils, biosolvents resulting from fermentation of sugar or starch from cereals, sugarcane and potatoes (for example, ethyl acetate, ethanol, butanol, etc.) and natural solvents deriving from lignocellulosic biomass (for example, d-limonene, α- and β-pinenes, etc.), but also supercritical fluids (for example, $scCO_2$) and green solvents (water under various forms: normal, subcritical, emulsions, etc.; *Table 2*).

4.2.1. *Supercritical Fluids*

Any substance is considered to be in a supercritical state if its temperature and its pressure are above their critical points, leading to modified properties: a supercritical gas display improved solubilizing properties, roughly similar to those of liquids, while presenting viscosities comparable to those of gas.[32] They hence display high diffusivity, a property that is particularly interesting when it comes to extraction process where the energy applied mainly serves to break the lipidic membranes to release the content of the plant cell. After extraction, the pressure release enables the easy recovery of the extracted molecules from the supercritical fluid, and the gas can be recycled through repressurization.[32] Supercritical fluid extraction (SFE) presents the advantage to generate extracts through a minimum of individual operations, leading in costs' reductions and better use of energy.[30]

Several gases display supercritical behavior (ethane, methane, ethylene, etc.), but their use for specific application may be impaired due to their inherent toxicity or their high supercritical temperatures, incompatible with the extraction of heat-sensitive compounds.[32] Supercritical fluids constitute an opportunity to produce eco-friendly extracts free of all traces of solvent, while being safe for the workers and the environment. Considering the whole process, and its global environmental impact, supercritical fluid extraction constitutes thereby a good alternative to traditional solvent extraction and steam distillation at lower operational cost, contrary to the general opinion (actual high initial investment but cost effective in the long run considering the whole process).[64] The main constraints limiting the implementation of SFE at the industrial scale is the difficulty to build units appropriate to resist to very high pressure (up to 1000 bar).[67]

At critical conditions for pressure (above 74 bars) and temperature (above 31 °C), CO_2 has the ability to behave like a fluid. Supercritical carbon dioxide ($scCO_2$) is a clean apolar solvent that can be used to recover compounds of low polarity from various plant matrices[17]; more or less similar to hexane or heptane in terms of polarity,[63,68,69] $scCO_2$ appears as a particularly interesting alternative to these solvents which use might be restricted or even forbidden for health and safety reasons in a very close future. Operated at lower temperature compared to conventional extraction methods, SFE using $scCO_2$ preserves the natural profile identity of the raw material and is particularly indicated to extract high added-value compounds that maybe heat-sensitive or thermolabile. Furthermore, $scCO_2$ can easily be eliminated simply by pressure release and recycled after extraction;[30] it is therefore adequate for the extraction of delicate fragrant constituents used for perfumes. The fluid's properties are easily modulated by simple variations of temperature and most of all of pressure: just above the critical pressure, the resultant extract is quite similar to an essential oil; by further pressure increase, the extract resembles more a concrete. However, $scCO_2$ extraction is not appropriate for the industrial extraction of fresh flowers containing more than 85 % H_2O (*w/w*) for both economic and logistic reasons; appropriately selected co-solvents may be used to circumvent such problems.[32,52]

Lavoine-Hanneguelle et al. used ethanol to extract fresh plants (*Jasminum grandiflorum*, *Jasminum sam-*

Table 2. Green and bio-based solvents as alternatives to petroleum solvents for extraction of fragrances (red cells: inappropriate for fragrance extraction; orange cells: may be appropriate but still not democratized; green cells: appropriate and/or already used for fragrance extraction).

Solvent		Origin/nature	Characteristics	Application to the fragrance industry	References
Agro-solvents	Methyl esters of fatty acids	Vegetable oils and butters (soya, cocoa, rapeseed, etc.)	Apolar; non-volatile; biodegradable; non-toxic; do not emit VOCs (volatile organic compounds); similar technical performances to petroleum-based solvents	Their boiling point is too high to remove these solvents after extraction, and therefore they could not be suitable to obtain pure fragrant ingredients.	[52]
	Bioethanol	Obtained by the fermentation of sugar-containing raw materials (sugar beet, cereals, sugar cane, etc.)	Easily available in high purity; low price; completely biodegradable	Largely use in perfumery for a long time for purification of concretes to absolutes.	[30]
	Terpenes	Extracted from pine (α-pinene) or citrus fruit (d-limonene)	Low polarity; very high solvent power; available in quantities	Their high boiling point and volatility which are similar to the ones of non-oxygenated terpenes make their application difficult. Some terpenes have been patented as solvents and possible use for specific application could be found in the future.	[30]
	Ionic liquids, Deep Eutectic Solvents (DES), Natural Deep Eutectic Solvents (NaDES)	Choline chloride-based NaDES; sugar (fructose, glucose)-based NaDES	Solvent power; non-polar; high chemical and thermal stabilities; non-flammable solvent; do not emit VOCs; considered to be safe solvents due to their lack of volatility that reduces any chance of exposure other than by direct cutaneous contact or by ingestion	Due to the potential toxicity of ionic liquids and DES, NaDES, displaying acceptable toxicity profiles, may present interesting selectivities to extract fragrant compounds. However, the recovery of the compound(s) of interest may require additional tedious step(s) to properly eliminate the extraction solvent. A solution would be to use NaDES to extract fragrant molecules and to use the resulting solution as the ingredient for fragrance formulation, instead of removing NaDES.	[30]
	Water		Non-hazardous profile; availability; low cost; reactivity (influenced by the H-bonds network); adjustable pH values; temperature-restricted liquid state; reactivity	May be considered as green, due to the use of water as solvent. However, the technique is highly solvent and energy consuming.	[53]
	Pressurized hot water or sub-critical water	By changing the temperature and pressure above 100 °C and 1 bar, the dielectric constant (ε) of water decreases and it is possible to tune it to be similar to the one of alcohol.	Physical and chemical properties of subcritical water are directly dependent on temperature and pressure, and therefore its solvent properties are strongly influenced and adjustable <u>ex:</u> from extremely polar at ambient temperature and	Industrial reactors are not yet approved for such extraction. Some degradation due to hydrolysis and temperature could occur, hence changing the natural extracts' profiles.	[30,53,61,62]

Table 2. (cont.)

Solvent	Origin/nature	Characteristics	Application to the fragrance industry	References
		pression (εr = ca. 80), water in a subcritical state at 250 °C and 4 MPa (εr = 27) presents properties similar to ethanol		
Supercritical fluids (ex: $scCO_2$)	CO_2 is under supercritical conditions when compressed at a pressure of up to 73.8 bar at a moderate temperature (31.1–40 °C). The addition of modifiers (for example alcohol) to CO_2 changes the properties, notably the polarity, of the extraction medium.	Odorless; colorless; non-toxic; non-flammable; rapidity; selectivity for volatile compounds; cleanliness; contaminant-free extract (longer shelf life of the resulting extract)	Already used to produce fragrant ingredients (several ingredients obtained using $scCO_2$ are already commercially available, *Table 3*).	[30,63 – 66]

bac and *Citrus aurantium* L. var. *amara* flowers) followed by CO_2 refining to obtain industrial flower extracts compared to traditional absolutes through panels evaluation: those new extracts were positively evaluated and appear to display fragrances quite different but nonetheless interesting from those traditional ones.[52]

Globally speaking, the construction of an SFE plant displays an environmental footprint roughly similar to the one of a conventional extraction plant. Similarly, SFE extraction process is quite comparable to conventional solvent extraction in terms of energy consumption but is significantly greener than hydrodistillation that requires huge amounts of water to warm up to perform the extraction, and to cool down at the end of the process. The main ecological advantage of SFE lies in the fact that supercritical fluids themselves constitute globally more virtuous models compared to petroleum-based solvents and water, but they are more expensive to produce, hence impacting the price of the end-product obtained. So, still very expensive (evaluated cost of 10000 euros per product for small volumes[52]), $scCO_2$ extracts have nevertheless become extremely popular during the last decade in the fragrance sectors and are often judged of finer scent compared to conventional products. Many of them are commercially available but the volumes produced still remain quite restricted. They have therefore totally integrated the perfumers' ingredients portfolio (*Table 3*),[54,65] and new ones are expected to be launched on the market, given that the technical equipment is more and more affordable.[62]

4.2.2. *Liquefied Gases*

Liquefied gases (sometimes referred to as liquid gases) are gases that have been turned into liquids by cooling them at atmospheric or reduced pressure down to their liquefaction point. Maintained at liquid state under pressure, they can be used as extraction solvents and are very easy to evaporate at the end of the process, leaving traces (less than 1 ppm, even than 20 ppb), if not no residues in the extract.[67] Gases were first liquefied to ease and secure their storage or transport: over the decades, they were used as refrigerant, source of energy (notably as fuel for natural gas vehicles), aerosols propellants, food sterilizer, etc.

The first use of liquefied gas to extract natural products dates back to 1930: Ebenezer patented a procedure to extract oils form oleaginous seeds. Liquefied gas have been used since 1940 to extract fragrant molecules from fragile raw materials, such as flowers.[67,71] Robertet, Inc. produced the so-called *Butaflors*, a series of highly concentrated extracts obtained with butane applied to the very delicate or heat-sensitive botanical materials, for example lilac, tuberose, lily of the valley, orange flower, gardenia, jasmine, rose, freesia, etc.[24,67,72]

One could observe a resurgence of interest for liquefied gases in the late 2000's. Extraction units enabling to perform solid/liquid extraction using liquefied gases have been implemented at the industrial scale. Two major systems have been designed: some units work in a thermodynamic mode, and

Table 3. CO_2 extracts commercially available for the perfume industry (non-exhaustive list[a]).[70]

CO_2 extract (commercial name)	Botanical name	Supplier(s)
Peanut CO_2 extract IFRA	*Arachis hypogaea*	SIPA A.CH. BERTHIER
Rooibos CO_2 extract	*Aspalathus linearis*	SIPA A.CH. BERTHIER
Encens CO_2 extrait	*Boswellia serrata*	Floral concept
Tea CO_2 extract IFRA	*Camelia sinensis*	SIPA A.CH. BERTHIER
Coffee Expresso CO_2 extract IFRA	*Coffea arabica*	SIPA A.CH. BERTHIER
Hazelnut CO_2 extract IFRA	*Corylus avellana*	SIPA A.CH. BERTHIER
Cardamome Extrait CO_2	*Elettaria cardamomum*	IFF-LMR Naturals Floral concept
Narcisse Absolu CO_2	*Narcissus poeticus*	IFF-LMR Naturals
Oakwood CO_2 extract IFRA	*Quercus robur* var. *sessiliflora*	SIPA A.CH. BERTHIER
Bourgeons de Cassis Extrait CO_2	*Ribes nigrum*	Floral concept
Schinus Molle Extrait CO_2	*Schinus molle*	IFF-LMR Naturals Floral concept
Pink pepper CO_2 extract	*Schinus terebinthifolius*	ALBERT VIEILLE IFF-LMR Naturals QUIMDIS SAS SIPA A.CH. BERTHIER
Vanille Bourbon Extrait CO_2	*Vanilla planifolia*	IFF-LMR Naturals
Ginger CO_2 SF extract	*Zingiber officinale*	IFF-LMR Naturals QUIMDIS SAS SIPA A.CH. BERTHIER

[a] Other CO_2 extracts are available from different suppliers (Firmenich SA, Mane, etc.).

others function on an isobaric mode, and both may even integrate a solvent recycling track.

In thermodynamic systems, solvent circulates through alternating compression and relaxation phases: liquefied gas is present in the extraction unit and is evaporated. Those vapors may be compressed again, and either be directly reinjected in the system to exhaust the raw material (semi-continuous mode) or be stocked for later use (batch mode). Due to the presence of a compressor, such units are really cumbersome and energy-consuming, and this observation is even more true for explosion-proof units; hence the existing thermodynamic units are usually of limited capacity ($<1\ m^3$) and are mainly used with non-flammable solvents.[67]

In isobaric systems, the solvent is all the time maintained in the liquid/gas equilibrium (the pressure in the system being directly linked to the system's temperature). Transition from liquid to gas only requires some heat provision, and in return cooling down is necessary for condensation. Both semi-continuous and batch modes can be used in isobaric systems which are more energy-efficient and less-expensive than thermodynamic ones. Actually, most of the manufacturers built their industrial units based on this model, as it is compatible with flammable solvents and not restricted in terms of capacity.[67]

In both systems complete elimination of the solvent requires relaxation and aspiration of the vapors while the plant material is mixed to gain access to all traces of solvent.[67]

Many gases can be liquefied, but to easily implement such extraction process at the industrial scale, a gas must satisfy to two main thermodynamic criteria: it should display a low boiling point comprised between $-30\,°C$ and $20\,°C$, easily reachable at atmospheric pressure, and a gentle vapor pressure, lower than 10 bar at ambient temperature. Combining selective extraction with easy solvent evaporation at the end of the process, make liquefied gases potentially suitable for extraction of thermo-sensitive or highly volatile compounds; the fact that they may be operated in such gentle conditions of temperature and pressure rapidly make them even more advantageous than $scCO_2$.[73] Several extraction processes using liquefied gases have been patented and commercialized over the last years.[74–76]

Once the noxious and greenhouse gases eliminated, less than ten liquefied gases can be reasonably used as extraction solvent at an industrial scale: among them, one can cite butane, propane, dimethyl ether (DME), 1,3,3,3-tetrafluoropropene and 2,3,3,3-tetrafluoropropene (respectively HFO-1234ze and HFO-1234yf, which are progressively replacing R134a

(1,1,1,2-tetrafluoroethane) characterized by a very high global warming potential due to greenhouse gases emission).[67,77,78] Rapinel et al. used a predictive model (COSMO-RS – COnductor like Screening MOdel for Realistic Solvents) to evaluate the lipophilic or hydrophilic character of those fluids (log $P \geq 0$; P corresponding to the octanol/water partition coefficient).[67,79,80] Propane and butane are good lipophilic solvents, but solubilize only few polar compounds, if at all. To a lesser extent, HFOs may be considered as lipophilic solvents.[67,73] Dimethyl ether appears as the most polyvalent solvent as it may extract both lipophilic compounds and more polar ones (oxygenated terpenes, polyphenols, etc.). This particularity is due to its partial solubility with water,[81] so DME can extract constitutive water from raw materials together with secondary metabolites.[67,82]

Nevertheless it is essential to notice that most of the hydrocarbon solvents (propane, butane, DME) derived from crude oils and present the disadvantage of being flammable, which implies their manipulation in dedicated area with ATEX (the ATEX name derives from the French title of the corresponding directive 'Appareils destinés à être utilisés en Atmosphères Explosives' and mean explosive atmospheres) compliant equipment.[67,83–85]

Fluorinated liquefied gas (HFO-1234ze, etc.) are very selective and present the advantages of being non-flammable and are often used preferentially for extraction of odorant molecules from natural raw material as the resulting extract is devoid of unwanted waxy compounds and bears a greater similarity to the original material than conventionally obtained extracts.[67,86,87] However, one should keep in mind that HFO-1234ze production by synthesis and its low biodegradability could constitute major impediments to its industrial use as a green alternative solvent;[88–90] more generally, a LCA appears necessary to decide whether or not a liquefied gas may be considered as a green alternative or not for a specific process.[89]

Natural extracts obtained through such processes and dedicated to the perfume industry do exist (*Butaflors*; cinnamon bark, savory and Madonna lily extracts were obtained using R134a,[31,91–93] etc.) but remain marginal nowadays for economic reasons.[62,67] In fact, such technology represents quite an investment: prices of liquefied gases are ranging from 1–2 k€/t (propane, butane, DME) to 17 k€/t (HFO-1234ze) and up to 200 k€/t for HFO-1234yf (tax free prices, INVENTEC Performance Chemicals, 2016).[67] Similarly, the cost of a 0.5 m^3 extraction unit may vary from 300 k€ to 500 k€ (comparatively, a $scCO_2$ extraction unit represents a 1 M€ investment for similar capacity).[67,94] Nevertheless, once implemented, such processes represent consequent energy savings, extraction time reduction, and better extraction yields, compared to a conventional hexane-extraction, and are also much safer for the operators and the end-users.[67,94]

4.2.3. *Agro-Based Solvents*

Agro-based solvents (or agro-solvents) obtained from biomass conversion are good candidates to replace progressively petrochemical solvents, as they are renewable, biodegradable, non-toxic and non-flammable and display a high solvent power.[30]

They present as well undisputable benefits in terms of global CO_2 emissions, security (transport, storage) and economic saving over the long term.[95] They may be obtained from conversion of:[23,96–98]

- **cereal and lignocellulosic biomass**: those solvents are obtained from natural fermentation of juices contained in sacchariferous plants (sugar beet, sugarcane) and from starchy resources (wheat, corn, barley); also referred to as biosolvents, those later are discussed into more detail in the next paragraph (see *Section 4.2.4*). Lignocellulosic residues from cereals and from sawmills can lead to the production of furfural;
- **oleaginous and proteaginous biomass**: those agro-based solvents consisting mainly in glycerol derivatives (for example glycerol carbonate, α,β-isopropylidene glycerol, etc.) and fatty acid esters are obtained from plant oils mainly (for example soya, sunflower, palm, linseed and rapeseed). Glycerol is the main by-product obtained by transesterification of triglycerides: it is a non-toxic, biodegradable and recyclable product that is largely used as a maceration solvent and can furthermore be easily converted into ethers and esters to generate innovative solutions to substitute glycols ethers conventionally used in the cosmetic, pharmaceutic and agri-food sectors.[98] However despite its promising physical and chemical properties (low price, large availability, renewability, high boiling point, negligible vapor pressure, environmentally-friendly, does not require special handling or storage), glycerol is not usable in the fragrance sector due to its non-volatility, implying the necessity to develop tedious processes to get rid of it at the end of the extraction and collect the extracted organic compounds;[98–101]
- **woody biomass**: obtained from wood, logging residues, fruit peel, etc., the main agro-based

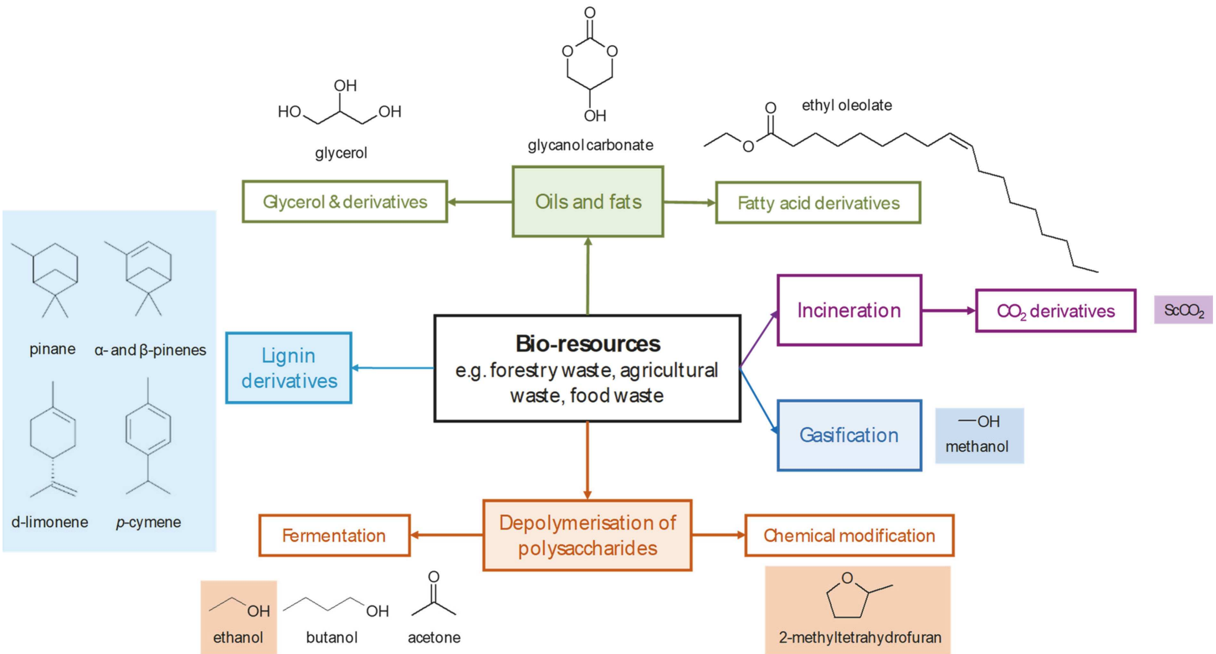

Figure 11. Some examples of bio-derived solvents (colored molecules: solvents presenting a potential interest in the fragrance industry).

solvents belonging to this category are terpenes extracted from pine (α- and β-pinenes) or from citrus fruits (d-limonene and *para*-cymene, resulting from oxidation of d-limonene).[97,102,103] Those terpenes display some physical and chemical properties similar to those of hexane, and can therefore easily constitute green substitutes to this solvent.[104] However, unsaturated terpenes are easily oxidized on air exposure and the resulting products may induce problems such as skin irritation or sensitizing, and may even be listed as contact allergens.[104–106] Hence, the hydrogenation of α-pinene and β-pinene to generate stable pinane that could be used as green alternative solvents might be a way to overcome this issue.[104] However, these solvents' volatility, quite similar to the one of the fragrant molecules of interest, may complexify their removal after extraction.

Although at first glance, the price of bio-based solvents is clearly higher than that of conventional ones, one should consider as compensation the costs associated with extraction efficiency, environmental compliance and health and safety issues.[95,96]

Agro-based solvents (*Figure 11*) are hence good candidates to substitute fossil-based ones but their use may still be limited to some sector for several reasons (cost, high viscosity, high boiling point); in fact, their use in the fragrance sector, may particularly be limited, if not totally avoided on a case by case basis, as some of them may generate off-flavors.[30,102]

4.2.4. *Biosolvents*

Biosolvents are conventional solvents obtained from renewable resources through processes integrating the green chemistry principles. Conventional solvents stemming from fossil resources (coal, natural gas and oil), may for most of them also be produced from bioresources through a biorefinery approach.

The ABE fermentation process leads to the production of acetone, butanol and ethanol (ABE), generated by the bacterial fermentation of plants containing sugar.[107–109] Simple sugars (either C5 and C6 sugars) contained in sugarcane or sugar beet, are directly fermented by a bacterial strain from the Clostridiaceae family. *Clostridium acetobutylicum*, sometimes called the 'Weizmann organism', after Chaim Weizmann who first used this strain to produce at the same time, acetone, butanol and ethanol from a sugary source, is the most widely species used to perform ABE fermentation, although promising results have been obtained using *Clostridium beijerinckii*.[110,111] More complex polysaccharides, such as starch (contained in cereals such as wheat, maize, barley) need to be hydrolyzed, either chemically or enzymatically, down to simple sugars (mostly glucose and maltose) which are then susceptible to yeast/bacterial fermentation. ABE Fermentation became generally non-profitable after World War II due to the higher costs registered for carbohydrate sources, compared to the efficient production of these three solvents by the petrochemical industry.[110] The health and safety issues inherent to fossil-based products have revived R&D efforts aimed at obtaining solvent from alternative sources.

About 95 % of ethanol used nowadays is produced from agricultural biomass: in 2008, roughly 40 % of this bioethanol production came from sugar crop processing and 60 % from starch crops.[112] Other bioresources containing mono-, oligo- and polysaccharides such as marine algae biomass have also been explored as sources of bioethanol.[113–115]

Bioethanol can then be used to produce butadiene and ethylene, which in turn can generate benzene, toluene, and xylene by acid-catalyzed oligomerization.[95]

In the 1940's over 60 % of the total butanol produced was obtained by fermentation,[116] but this number decreased with ABE fermentation falling out of use as already mentioned. Advance in modern technology finally allowed the ABE process to be competitive against petrochemical synthesis and one could witness a resurgence of this process in the 2000's: several biobutanol production plants have been constructed over the world.[109,117]

Biobutanol displays a polar solvency characteristic of alcohols, but unlike other alcohol, it is less flammable and displays higher viscosity.[118] It is not a solvent of concern regarding toxicity and is even considered as GRAS (Generally Regarded As Safe) by the Flavor and Extract Manufacturers Association (FEMA), United States. Biobutanol was notably used to extract peppermint, citrus and lavender and the resulting extracts display comparable odorant profiles to the corresponding ethanol extracts, hence demonstrating biobutanol's applicability as an effective, yet overlooked, alternative solvent for the extraction of lipophilic molecules.[109] However, its low volatility may impair its generalized use in the fragrance sector.

Many other molecules can be classified into biosolvents: further glucose fermentation leads to the production of sorbitol, lactic acid esters, succinic acid derivatives, etc.; again, volatility issues impede their application to extract volatiles components for the perfumery industry.

Lignocellulosic biomass can be converted to biosyngas (shortcut for synthetic gas) containing predominantly H_2 and CO through gasification, which in turn can among others be converted into biomethanol, bioethanol and hydrocarbons.[119] Syngas conversion using microbial fermentation is another potential route to produce bioethanol.[108]

The production of biodiesel from plant oils for the bio-derived fuel industry generates glycerol, an organic waste that can be valued directly as a green solvent or be further converted into several other chemicals.[56,96,99] The non-volatility of glycerol and the necessity to develop protocols to eliminate it at the end of the process, already discussed previously, impairs its used for the extraction of volatile molecules.

Extensive efforts have also been put in the production of liquid hydrocarbons from biomass feedstock, but many of the resulting biosolvents are still VOC solvents, flammable and even toxic, so even if they are already more sustainable compared to their petrochemical counterparts, those biosolvents do not constitute the ultimate solution for the perfume industry.[96]

4.2.5. *Ionic Liquids, DES and NaDES*

Ionic liquids (ILs) are non-aqueous salt solutions, and contrary to ordinary liquids predominantly made of electrically neutral molecules, ionic liquids are largely made of ions. Ionic liquids are non-flammable due to their low vapor pressure and remain liquid at moderate temperatures (0–140 °C).

In green chemistry, ILs have been used for diverse purposes including for the extraction of natural compounds from biomass:[120] ILs were notably successfully combined with microwave-assisted extraction (ILMAE) to extract medicinal alkaloids from lotus leaf[121] or polyphenolic compounds from medicinal plants,[122,123] or with ultrasonic-assisted extraction (ILUAE) to extract piperine from white pepper.[124] Such IL-based method are particularly advantageous as the required extraction time may be significantly reduced through the combinational use of intensification techniques.[125] ILs made of hydrophobic constituents have been used to extract flavors, fragrances and essential oils instead of conventional steam distillation.[125,126] However, their 'greenness' is often questioned, due to their poor biodegradability and sustainability and their assessed toxicity.[127,128] Furthermore, their very high viscosities and the efforts required for their synthesis might hinder their widespread applications.[53]

The so-called DESs (Deep Eutectic Solvents) constitute an alternative to ILs. They consist in mixtures of two or more solid or liquid components, that at a

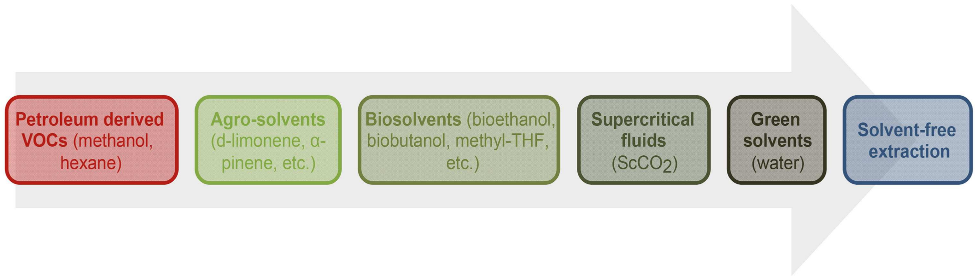

Figure 12. Towards green alternative solvents for the fragrance industry.[46]

particular composition present a high melting point depression, becoming liquids at room temperature.[127] As ionic liquids, DESs display very low vapor pressure and are therefore non-flammable. Their toxicity and biocompatibility are thought to be dependent on the ones of the individual components they are made of; it is therefore possible to obtain eco-friendly versions displaying both low toxicity and high biodegradability.[129] Their relatively high viscosities together with the fact that most DESs remain solid at room temperature, however might hinder some of their industrial applications.

DESs are called NaDESs (Natural Deep Eutectic Solvents) when they are bio-based, that is, when both their components are plant primary metabolites (for example small organic acids or bases, sugars, alcohols, amines and amino acids) that in different combinations and specific molar ratios form liquids at ambient temperature.[120,130]

NaDES fully integrate green chemistry principles: they are sustainable, highly biodegradable, display acceptable toxicity profiles, and present the advantages of their low cost, and their simple preparation.[130,131] Furthermore, they possess a real potential to be considered as green solvents for extraction as they display high solubilization power of both polar and nonpolar molecules.[130] Their polarity ranging between that of water and alcohols, they have been reported to extract a wide variety of compounds from plant origin: NaDES have already been used to extract phenolic compounds from safflower or anthocyanins from rose periwinkle.[120,131,132] González et al. (2017) replaced conventional hydroalcoholic mixtures with NaDES to extract vanillin from vanilla pods to obtain an extract intended for the flavor sector: all the tested NaDES tested display a higher extraction capacity for vanillin than ethanol and methanol and provide the additional benefit of an increased stability of vanillin.[120] These authors concluded that thanks to their high extraction capacity and the absence of toxicity of their individual components, NaDES may be very suitable for extraction of flavors and fragrances used in food and cosmetics, then at least at the laboratory scale.[120] In fact, the recovery of the volatile compounds of interest still requires additional tedious step(s) to properly eliminate the extraction solvent.

The NaDESs' unique properties open interesting perspectives and there is no doubt that they will constitute great contributions to develop sustainable industrial processes even for the pharmaceutical, cosmetic/fragrance, and food sectors, as they can comply with the strict regulations governing those later, but there is still a long way to go towards their industrial applications.[125,133,134]

Two properties of NaDES that may limit their widespread use are their high viscosity and negligible volatility implying the difficulty to eliminate them at the end of the extraction process as they cannot be evaporated. Several recovery methods have already been successfully applied to circumvent these problems at the laboratory scale, but so there is room for technological improvement to turn these disadvantages into advantages.[125,135]

4.2.6. *Conclusion*

Lots of greener alternatives to petroleum-based solvents exist, but a detailed Life Cycle Assessment would be necessary to claim their individual suitability for specific applications (fragrances (*Figure 12*), flavors, etc.) from a 'green chemistry' point of view. The development of solvent-free extraction methods appears however the ultimate alternative, for many reasons: avoiding the use of large volumes of solvent is safer (reduced risks of overpressure and explosions) and cheaper, the scale-up of such methods is facilitated, and the resulting extract is of higher purity (no traces of residual solvent).[136]

4.3. *Processes' Intensification Technologies*

Conventional extraction processes usually require massive energy consumption. Among routes to minimize this energy consumption, one can assist existing processes with intensification technologies to produce high-quality innovative fragrance extracts.[30] Activation technologies, and more particularly microwaves, furthermore enable the development of solvent-free industrial processes, an even more advantageous and greener alternative.

4.3.1. *Pressurized Fluid Extraction* (PFE)

Pression maybe an interesting parameter to modulate to intensify laboratory processes: three methods of pressurized fluid extraction are particularly elected by the R&D community, that is, supercritical fluid extraction-SFE (already presented in this article); Pressurized Solvent Extraction-PSE (also referred to as Accelerated Solvent extraction-ASE, Pressurized Liquid Extraction-PLE, or Subcritical Solvent Extraction-SSE); and Pressurized Low Polarity Water-PLPW extraction (also known as subcritical water extraction, Pressurized Hot Water Extraction-PHWE or SuperHeated Water Extraction-SHWE).[137]

PSE is an affordable method largely used at the laboratory scale to extract various chemicals from a complex solid matrix.[138] PSE is usually performed with organic solvents (mainly hexane, methanol or ethanol) that can be quite easily removed at very low traces level at the end of the process.[51,139] The process uses high temperature (50–200 °C) and pressure (500—3000 psi), which results in shorter extraction time, reduced solvent consumption, and higher extraction yield.[137,140] Elevated temperatures increase the extraction efficiency whereas elevated pressure keeps the solvent in a liquid state as the temperature is set above its boiling point.[141] High pressures also facilitate the access of solvents to areas of the plant matrix that could not be reached at atmospheric pressure.[141] However, high temperatures precludes PFE use for extraction of heat-sensitive compounds.

PSE can be performed in both static and dynamic modes. In static mode, the sample is enclosed in a stainless-steel cell. Solvent is pumped in this extraction unit and is allowed to equilibrate under those static conditions for a predetermined time. The extract is then purged into a collection vial after extraction. Multiple re-extractions of a sample can be performed. In dynamic systems, solvent is continuously pumped through the sample, hence using larger volumes of solvent and consequently diluting the extract.[140]

PFE is considered as an environment-friendly technique, as it generates small volumes of waste and implies reduced costs and extraction time. PSE was notably used by Dawidowicz's team and compared to other techniques (Soxhlet, distillation, SFE, etc.) for the isolation of essential oil components of *Thymus vulgaris*.[142] However, this technique is still explored at a laboratory scale, and there is a long way to go to develop production units.

PLPW extraction, using pressurized hot water as a solvent, is even a greener version of PSE.[143] Water is a polar solvent, but if maintained in a liquid state by pressure application it may be quite versatile: once heated up to 200 °C, its dielectric constant drops from 79 to 35, and water hence displays properties similar to those of ethanol or methanol.[137,144,145] The parameters at which PLPW extraction is performed depend on the nature of the compounds of interest to extract and on their further application, but such high temperatures are incompatible with the use of such technology for the extraction of sensitive odorant compounds.[145]

Not to mention the difficulties of designing suitable production devices able to operate on a continual basis under both high pressure and temperature, it is not surprising that PFE technology is not currently valorized at the industrial level, given all the technological challenges encountered. Industrial scale SFE devices already exist and may pave the way for further instrumentation scale-up for 'younger' technologies, that is, PLPW extraction and PSE.[137]

4.3.2. *Ultrasound-Assisted Extraction* (UAE)

Ultrasound can be divided into *diagnostic ultrasound* (characterized by frequencies ranging from 100 kHz and 1 MHz) and *power ultrasound* characterized by high intensity and low frequencies (comprised between 16 kHz and 100 kHz); this later portion of ultrasound can be involved, through the cavitation phenomenon, in extraction and processing applications.[146–148]

This cavitation effect leads to the formation in the solvent of microscopic air bubbles/cavities which size and shape oscillate in response to the successive compression/relaxation cycles to finally reach an unstable size and implode violently if the acoustic pressure is high enough (*Figure 13*). This collapse generates mechanical forces which lead to the disruption of biological cell membranes and in subse-

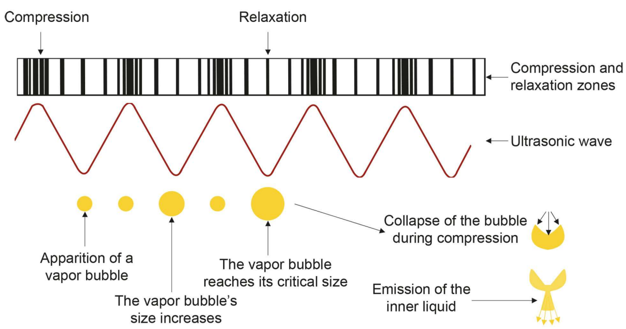

Figure 13. Principle of Ultrasound-Assisted Extraction.

quent release of their content which diffuses from the matrix into the extraction solvent.[26,146] UAE processes can be performed with almost any extraction solvent (water, alcohols, oils, hexane, etc.).

UAE may be used alone, or in combination with other techniques. For example, Hu et al. (2007) used UAE coupled with supercritical fluid (Ultrasound assisted Supercritical Fluid Extraction-USFE) to extract oil from adlay seeds and observe that the assistance of ultrasound leads to a reduction of the extraction time and an increase of the extraction yield.[149] The ultrasound-assisted hydrodistillation constitutes a more efficient version than the conventional method to obtain essential oils with higher extraction yields, while considerably reducing extraction time and energy used.[26,30]

Although costly, ultrasound can enhance extraction process and UAE units have been implemented at the industrial scale, notably in the food industry, but remain quite modest in terms of capacity compared to their conventional counterparts (*Figure 14*).[26,62] A mean to circumvent this 'volume' issue, would be to develop UAE industrial units functioning on a continuous mode, rather than on a batch mode as actually available on the market.

Figure 14. Ultrasound-Assisted Extraction unit.

UAE is mainly used at the industrial scale in the aroma sector. Most of the aromas' compounds hence extracted have an immediate use (for instance, in liquor production) or can be employed as food or cosmetic additives (for example essential oils and single molecules with specific activity). GMC (www.gmariani.it) is an Italian company specialized in the extraction of aromatic herbs, that adapts their extraction systems, either conventional or innovative, depending on the characteristics of the herbs of interest. GIOTTI (www.giotti.it) is another Italian company that uses ultrasonic assistance to extract food, or pharmaceutical additives, and to produce alcoholic drinks. This company works with four continuous batch systems equipped with ultrasound on each side of the tank and an agitation system. Moliserb s.r.l (www.moliserb.com) is specialized in ultrasound-assisted extraction of thermolabile compounds with alimentary and cosmetic applications. The only application of ultrasounds in a continuous extraction process has been reported by Cavitus, an Australian company (www.cavitus.com) that uses ultrasound to enhance the maceration during wine making to increase the tannins, anthocyanins and aromas' content of the resulting product. Finally, if direct UAE applications in the aroma industry are quite numerous, one could not say the same for the fragrance industry, even both sectors are quite close.

4.3.3. *Microwave-Assisted Extraction* (MAE)

Microwaves are radiations comprise between X-rays and infrared rays which are characterized by frequencies between 300 MHz to 300 GHz.[150] Microwave heating, also known as dielectric heating or high-frequency heating, is the process in which a microwave electromagnetic radiation heats a dielectric material, through the molecular dipole rotation within the electric field (*Figure 15*). The electric energy brought to the system is converted through this rotation, into kinetic energy which in turns is converted into heat: the dipole alignment with the electric field is continuously impeded by molecular interaction forces (Van der Waals bonds, hydrogen bonds), hence generating molecular frictions, and subsequent heat. In microwave heating, the heat transfer occurs from the inside to the outside, that is, it is inverted compared to conventional heating.[8]

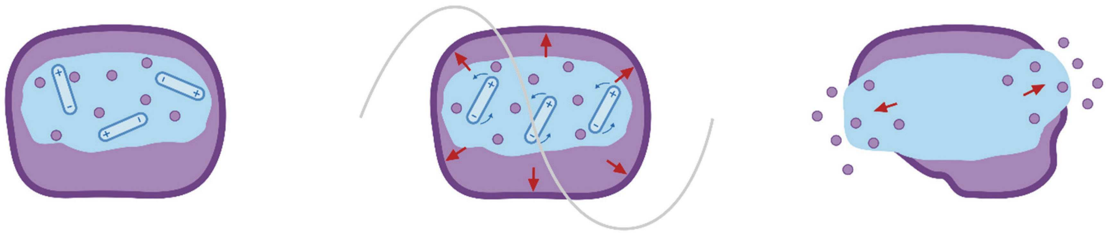

Figure 15. Mechanism of microwave extraction of essential oils based on dielectric heating.

Hence, only dielectric materials and solvents with permanent dipoles get heated up under microwave;[151] the ability of a solvent to absorb microwave energy is characterized by its dielectric constant ε.[150]

The use of microwaves to assist extraction was first described in 1986.[152] Microwaves can be effectively used to extract natural compounds from all sorts of plant materials (wood, seeds and leaves) with significant time and energy savings.

MAE is largely used to extract essential oils from lots of plant species:

Microwave Hydrodiffusion and Gravity (MHG) performed at atmospheric pressure without any solvent, combines microwaves exposition to promote the release of internal water of the plant matrix, to earth gravity to recover essential oils and other valuable products from the bottom of the reactor through condensation of the distillate.[153,154] The resulting extracts are obtained with higher extraction yields and are free from any residual solvents, contaminants, or artefacts. Extraction times being considerably shortened, such system is environmentally friendly.[154]

The microwave-assisted dry distillation process used to extract essential oils from fresh plant material, referred to as Solvent-Free Microwave Extraction (SFME), is another example of such solvent-free processes that could be largely democratized in the fragrance industry, as an alternative to the conventional water- and energy-consuming hydrodistillation.[155,156] This technique combines microwave heating and distillation performed at atmospheric pressure without any solvent addition. The heating of the in situ water distends the plant cells, leading to the rupture of oleiferous glands, and consequently freeing essential oil which is evaporated together with this in situ water. A cooling system outside the microwave continuously condenses the vapors which are collected in a dedicated glassware.

Although solvent-free conditions are a quite desirable green option, in many cases, a solvent is required to assist in working up processes. MAE can also be performed with solvent (provided that it absorbs microwaves): the homogenized plant matrix is mixed with a polar or apolar solvent and the suspension is then exposed to microwave irradiation.[145] This irradiation causes the steam-induced 'opening' of the matrix and promotes the extraction of secondary metabolites.[32]

Polar solvents such as ethanol and methanol undergo lesser microwave absorption then water due to their lower ε values but their overall heating remains efficient.[150] Hexane and other less polar solvents are transparent to microwaves and hence do not produce any heat.[157] This property of solvents frequently used in perfumery is particularly interesting as it avoids thermodegradation of specific compounds of interest.

MAE units (*Figure 16*) have progressively been implemented at the industrial scale. Such a system has been used by PELLAS (http://pellasnature.com/) to aromatize olive oil with aromatic herbs and spices. The company is able to produce 100 000 liters of aromatized olive oil per MAE unit (MAC 75 from Milestone). Gattefossé (www.gattefosse.com/) uses MAE technology to extract essential oils but also in situ water from aromatic herbs, flowers and fruits.

5. Modern Techniques in Perfumery: Applications and Discussion

As already stated, end-consumers, and therefore industrial sectors, increasingly place a premium on naturalness. However, the definition of genuine natural extract remains unclear. According to the REACH legislation, a natural substance is 'a naturally occurring substance as such, unprocessed or processed only by manual, mechanical or gravitational means, by dissolu-

Figure 16. Microwave-assisted extraction unit.

Figure 17. Characteristics defining an 'eco-extract'.

tion in water, by flotation, by extraction with water, by steam distillation or by heating solely to remove water; or which is extracted from air by any mean'.

In this context, the ISO 16128 standard provides guidelines for technical definitions and criteria for natural and organic cosmetic ingredients and products. In addition, naturalness is very often associated to'organic' aspects. For example, Ecocert and Cosmos certifications are essential in the cosmetic sector and deal with both aspects. They are associated to detailed guidelines governing the chemicals and solvents authorized as well as the processes and facilities adapted to produce certified organic and natural extracts or products.

Various other appellations or labels referring to naturalness may in specific industrial sectors be found on extracts or final products' packaging. Each of them is associated to a specific charter of good practices, relating to the type of raw material, chemicals, processes and additives authorized. All these labels aim principally at reassuring consumers about the product's naturalness and intrinsic security.

To meet the challenges of naturalness, innovative techniques and green solvents are of great interest for numerous industrial sectors to make a move towards Green Extraction or Eco-Extraction. To be considered an 'eco-extract', such extract must display the following characteristics (*Figure 17*): they must be natural and of high quality (that is, be constituted of active and undenatured compounds), and should display high functionality (antioxidant, antimicrobial, flavoring or coloring properties, etc.) in accordance with the specific legislation governing the sector of application (agri-food, cosmetics, pharmaceutical industry, etc.), while presenting a low environmental footprint (determined using the LCA approach).

Regarding more specifically the fragrance sector, most of these new solvents evocated are quite promising (NaDES, some liquefied gases and agro-solvents, etc.), but their generalized use is impaired for most of them by costs related to the sourcing of raw material, but also due to their low volatility preventing their easy removal at the end of the extraction process. Lots of the innovations mentioned in this review have been largely explored at the R&D scale but remain quite far from a real application in perfumery. Actually, $scCO_2$ extracts are the only eco-extracts that are commercially available and which use has already been integrated in perfumers' creative processes.

Similarly, activation techniques (that is, ultrasound- and microwave-assisted technologies), largely explored at the laboratory scale, are probably the most promising processes nowadays to produce fragrant extracts but taking a step back from the bench to look at the bigger picture, their industrial implementation is still restrained due to units' volume and cost issues.

6. Conclusion and Perspectives

Extraction of odorant substances translated from empiricism to real science over centuries. Hydro- and steam distillations, as well as extraction using volatile solvents, remained standard techniques for very long, but environmental constraints drove to compulsory technical innovation and developments of innovative processes.[62] In fact, industry had to adapt as consumers grow more environmentally-conscious and more discriminating in their products' choices, particularly when those later have to be applied on their skin: in the consumers' minds, 'natural' equals 'safety' and 'healthy'. Naturality becoming mainstream, after decades of growth based on inexpensive synthetic molecules made available by chemistry, the global fragrance industry, just as many other sectors at the same time, is slowly but inevitably changing towards sustainability and is urged to drive innovation in consumers' goods. Forced towards this post-petroleum era, the fine fragrance industry has started to investigate (and invest in) new extraction technologies to meet the rapidly increasing demand of new natural ingredients, while slowing down the unsustainable use of resources. Eco-extraction processes and agro-based solvents, together with appropriate sourcing strategies, constitute real sustainability levers to propose ecologically sound ingredients for the fragrance industry without compromising on sensory experience,[158] and there is still room for new technologies in the rapidly evolving fragrance industry. In fact, many of the new solvents and technical innovations presented in the review are particularly appealing but apart from the SFE, their industrial applications remain anecdotal. No data regarding LCA of such technologies and such extracts could be found in the literature, even though they would constitute crucial marketing arguments to drive sustainable-minded consumers towards such innovative process and ingredients.

However, as science and technology further advance, new fragrant ingredients emerge, with their own olfactory specificities, and should not be considered as reinterpretations of existing ingredients. The perfumer's portfolio expands consequently, and in a sector that remains quite traditional, professionals have to adopt those new ingredients and to learn how to create new contrasts with these new building blocks. However the use of EOs, absolutes and extracts obtained with such modern techniques is still not democratized, mainly for important pricing reasons.[62] Cost allowances for formulas directly affect quality: fragrance project briefs have to take into account the higher prices of such technological raw materials to be realistic.[159] Is there a way to make those available at a lower cost or will such materials remain accessible only to the restrictive niche perfumery, less constrained by ingredients' cost VS. volume issues?

So, despite their interests, it is quite unlikely such modern technologies and green solvents established themselves as unescapable solutions for the fragrance sector in a near future. However, several facts could make the difference and really accelerate the pace to inject innovation into this sector:

- innovative technologies would lead to new eco-extracts/ingredients with particular olfactory profile: such original ingredients could make their way towards the niche perfumery, a sector that might be easier to invest, as required supply volumes of extracts remain quite restricted (hence being compatible with today's production capacities of these innovative techniques) and as related-costs might be less constraining. Niche perfumery is also a segment more used to risk-taking in terms of olfactory profile that could integrate an eco-extract to one creation instead of the conventional one stemming from the same raw material, for its olfactory particularity. The potential commercial success of the perfume created could drive more conventional perfume houses to use such specific eco-extract. By a snowball effect, such integration of eco-extracts in perfumes may lead to the development of the corresponding technology and to the inherent decrease of the resulting extracts' prices;
- in a constantly evolving regulatory environment, the perfumer's portfolio is susceptible to major changes in the future and eco-extracts/greener fragrant ingredients could then find their niche in comparison with the present situation where certain raw materials remain tendentious (due to the presence of some chemical components). The flexibility of the perfumer's creativity appears to be more crucial than ever to adapt oneself to the constantly evolving sector;[160]
- such eco-extracts/greener ingredients could also dig in the market through an indirect way: their use could be democratized first in interrelated domains less constrained by olfactory properties. For example, aromatherapy is a sector mainly driven by bioactivities, rather than by olfactory concerns : an

essential oil produced by microwave-assisted extraction, that is, an essential oil of lower ecological footprint, could display similar or even higher biological activities (due to chemical composition differences) compared to the ones of the conventional essential oil produced from the same raw starting material, and could then be preferentially used in this domain. Hence, the democratized use of innovative extracts in such interrelated domains may hence lead to the development of the corresponding technology and to the subsequent decrease of costs of the resulting extracts, which could then progressively invest the fragrance sector.

As reviewed in the present article, numerous innovative technologies are currently explored to democratize the development of sustainable natural ingredients coherent with today's green-minded consumers concerns, but there is still a long way to go to propose viable alternatives to conventional odorants, which could really make their way to integrate sustainability into the perfumer's palette on a permanent basis.

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Author Contribution Statement

P. Burger conducted a comprehensive literature review and wrote the article along with H. Plainfossé. X. Brochet, F. Chemat and X. Fernandez revised and proofread the manuscript.

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