Peer-reviewed version available at *Technologies* **2020**, *8*, 45; doi:10.3390/technologies8030045

Article

Microwave Extraction vs. Other Techniques for Industrial Scale Cannabis Extraction

Marilena Radoiu [1,2,*], Harmandeep Kaur [1], Anna Bakowska-Barczak [1] and Steven Splinter [1]

[1] Radient Technologies Inc., Edmonton, Canada; mradoiu@radientinc.com
[2] Microwave Technologies Consulting, Lyon, France ; mradoiu@microwavetechs.cm
* Correspondence: mradoiu@microwavetechs.com; Tel.: +33 651 285174

Abstract: Cannabis is a flowering plant that has long been used for medicinal, therapeutic, and recreational purposes. Cannabis contains more than 500 different compounds, including a unique class of terpeno-phenolic compounds known as cannabinoids; Δ^9-tetrahydrocannabinol (THC) and cannabidiol (CBD) are the most prevalent cannabinoids and have been associated with the therapeutic and medicinal properties of the cannabis plant. In this paper, continuous flow microwave assisted extraction (MAE) is presented and compared with other methods for commercial cannabis extraction. The practical issues of each extraction method are discussed. The main advantages of MAE are: continuous-flow method which allows for higher volumes of biomass to be processed in less time than existing extraction methods, improved extraction efficiency leading to increased final product yields, improved extract consistency and quality because the process does not require stopping and restarting material flows, and ease of scale-up to industrial scale without the use of pressurised batch vessels. Moreover, due to the flexibility of changing the operation conditions, MAE eliminates additional steps required in most extraction methods, such as biomass decarboxylation, winterisation, which typically adds at least a half day to the extraction process. Another factor that sets MAE apart is the ability to achieve high extraction efficiency even at the industrial scale. Whereas the typical recovery of active compounds using supercritical CO_2 remains around 70-80%, via MAE up to 95% of the active compounds from cannabis biomass can be recovered at the industrial scale.

Keywords: cannabis; THC; CBD; microwave assisted extraction, continuous flow

1. Introduction

Cannabis is a genus of flowering plants belonging to the cannabaceae family with three main species: *Cannabis sativa*, *Cannabis indica*, and *Cannabis ruderalis*, Figure 1 [1].

Peer-reviewed version available at Technologies 2020, 8, 45; doi:10.3390/technologies8030045

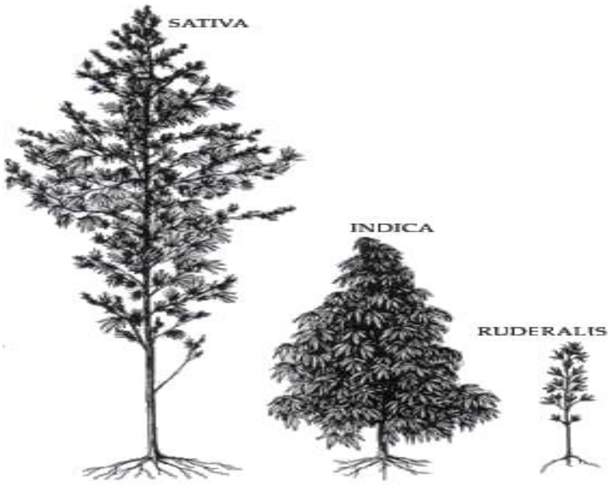
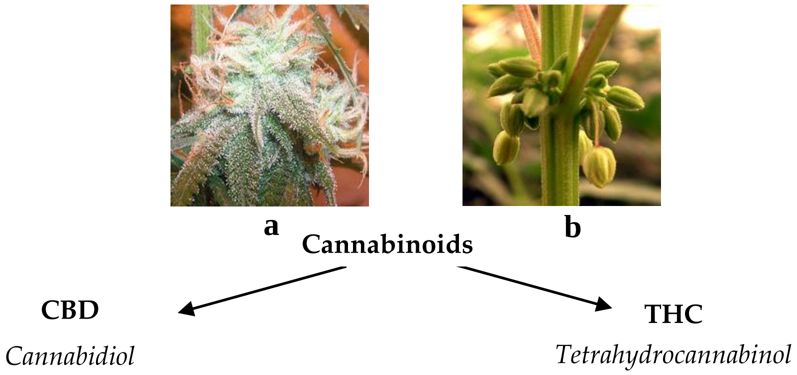


Figure 1. Cannabis plant [1]

Cannabis has a long history of being used for medicinal, therapeutic, and recreational purposes. Cannabis is known, for example, to be capable of relieving nausea (such as that accompanying chemotherapy), pain, vomiting, spasticity in multiple sclerosis, and of increasing appetite. The importance of cannabis in therapeutics is emphasized by the ever-increasing number of research publications related to the use of cannabis and cannabis products to treat various indications [2-5].

Cannabis contains more than 500 different compounds, which include terpenes, flavonoids, lipids, sterols, chlorophyll, fatty acids, salts, sugars, and a unique class of terpeno-phenolic compounds known as cannabinoids or phytocannabinoids. More than 100 cannabinoids have been identified in different cannabis plant strains. Examples include Δ9-tetrahydrocannabinol (THC), cannabidiol (CBD), cannabinol (CBN), cannabigerol (CBG) and cannabichromene (CBC) [5-7]. THC and CBD are the most prevalent cannabinoids and have been associated with the therapeutic and medicinal properties of the cannabis plant and associated products – Figure 2. THC is mainly recognized for its psychotropic effects when consumed, but lately has also been found to effectively treat pain, muscle spasticity, glaucoma, insomnia, lack of appetite, nausea, and anxiety while CBD is used to treat migraines, inflammation, seizures, IBS, depression, insomnia, and anxiety [2,3,8]. CBD is non-psychoactive and is the major cannabinoid constituent in hemp cannabis.

The terms hemp and marijuana are classifications of cannabis adopted into culture even though they do not represent legitimate nomenclature for cannabis. Hemp and marijuana are both cannabis; hemp, however, refers to cultivars of cannabis that contain very low concentrations of psychoactive THC (typically less than 0.3% by dry weight). Hemp (sativa) is an industrially grown plant that is cultivated outdoors, better suited for warm climates with a long season. Industrially grown hemp is used to produce textiles from the hemp fibre, and foods and supplements such as protein and essential fatty acids from the seeds. Hemp seed oil is rich in unsaturated omega-3 and omega-6 fatty acids and is almost entirely devoid of cannabinoids. Marijuana, on the other hand, is often deliberately bred and cultivated in controlled environments in order to optimize the cultivar's characteristics, including the composition of cannabinoids such as THC and CBD. Controlled growing and cultivation is designed to produce female plants that yield budding flowers rich in cannabinoid content. Harvesting of industrial hemp has traditionally avoided collection of flowers to minimize cannabinoid content of industrial products. This practice is however changing as the production of CBD from farmed hemp becomes legalized in more and more jurisdictions world-wide.



CBD is the functional compound in cannabis. It is not psychoactive, so no dose limit was imposed on it use. It is reported to have anti-inflammatory and pain-killing properties. It works best in combination with THC.

THC is the psychoactive, compound in cannabis. It is largely illegal around the world, or legal on prescription only, although recreational use is beginning to be legalised in some countries.

Figure 2. Main cannabinoids in cannabis sativa plant; (a) Female flower with visible trichomes; (b) - male cannabis flower buds [9]

Cannabinoids are particularly concentrated in the glandular hairs (trichomes) distributed across the surface of the cannabis plant. These trichomes are particularly concentrated in the bracts and leaves of the female inflorescence. Resin glands form at the tips of these trichome stalks and secrete an aromatic terpenoid containing resin with a very high content of cannabinoids.

The proportion of cannabinoids in the plant may vary from species to species, as well as vary within the same species at different times and seasons. Furthermore, the proportion of cannabinoids in a plant may depend upon soil, climate, and harvesting methods. Thus, based on the proportion of the cannabinoids present in a plant variety, the psychoactive and medicinal effects obtained from different plant varieties may vary.

Historical delivery methods of cannabis have involved smoking, *i.e.* combusting, the dried cannabis plant material [10]. Smoking results, however, in adverse effects on the respiratory system via the production of potentially toxic substances. Alternative delivery methods such as oral administration of edible forms, transdermal delivery of topical forms and buccal administration of sprays for oral or nasal administration all require some method of extraction of the cannabinoids and other compounds from the plant.

North America is experiencing a boom for cannabis-derived products (*i.e.* packaged foods, edibles and beverages, beauty & personal care, consumer health, pet care, home & garden), made possible by the legalization of recreational cannabis in Canada in 2018 and in 11 U.S. states, two U.S. territories, and the District of Columbia. The global market for cannabis-derived products was ~ 5 trillion USD in 2018 and is expected to grow 1,200% by 2023 [11].

To this end, there are various conventional biomass extraction methods available for the extraction of cannabis. Given the inherent commercial value of CBD and THC, the applied method

Peer-reviewed version available at *Technologies* **2020**, *8*, 45; doi:10.3390/technologies8030045

to extract them is very important in terms of accomplishing the quantity and quality of the product. Moreover, economics of the processes is a very important parameter in its commercialization.

The scope of this paper is to present an overview of the extraction methods currently used commercially for cannabis extraction with particular attention to the relative advantages of continuous flow microwave-assisted extraction.

2. **Commercial Cannabis Extraction Methods**

There are several important considerations to consider when choosing an extraction method for cannabis. The most important are as follows:

- *Extraction efficiency*, the percentage of bioactive compounds recovered through the entire extraction process;
- *Extract quality and consistency*, including the purity or "potency" of cannabinoids in the extract and also the relative amounts or "profile" of other potentially synergistic compounds such as terpenes;
- *Throughput capacity and scalability*, assessment of the extraction method and its efficient implementation at commercial scales vs. market demand;
- *Environmental control*, *e.g.*, carbon footprint and *safety*, *i.e.* minimize risks to the consumers and worker safety.

The potency (a term often used *in lieu* of purity or concentration) of cannabis extracts and extract-derived products is equivalent to cannabinoid (*e.g.*, Δ^9-tetrahydrocannabinol, THC) content. Depending upon the psychoactive and medicinal effects obtained from different varieties of the cannabis plant or the different methods of cultivation for cannabis, a specific variety of cannabis may be considered more effective or more potent than others (*e.g.*, in providing the desired physiological effect at a desired level in an individual). Similarly, some specific combinations of pharmacologically active compounds in a cannabis variety may be more desirable in comparison to other varieties. When preparing cannabis plant extracts, the retention of the full mix of cannabinoids present in the original plant may be desirable for some varieties, while other varieties may be preferred in altered form due to the variances in the specific cannabinoid composition and concentrations. Such variance is further exacerbated by the presence of certain terpenoid or phenolic compounds, which may have pharmacological activity of their own and which may be desired at different concentrations in different combinations.

In many cases, additional processing steps, both upstream and downstream of the extraction itself, are required to obtain the final cannabis extract product. The incorporation of these steps with the extraction method and their impact on the overall process efficiency and product quality must also be considered. Some common processing steps discussed further below include:

- *Decarboxylation*, the process of converting non-active native acidic cannabinoids into their active, neutral forms via a thermal reaction;
- *Winterization*, the process of removing plant lipids and unwanted waxes by a secondary solvent, freezing and filtration;
- *Decolorization*, the process of removing chlorophyll and unwanted pigments;
- *Secondary purification*, the process of further purifying the extract to increase the potency of cannabinoids and other components, via various methods including distillation, chromatography, or crystallization.

Peer-reviewed version available at Technologies 2020, 8, 45; doi:10.3390/technologies8030045

The cannabinoids are biosynthesized in the cannabis plant in acidic forms known as acidic cannabinoids. To be therapeutically active, these acidic cannabinoids must be converted to their neutral forms by a decarboxylation reaction. Decarboxylation is instant when cannabis is combusted during smoking [12]. All other consumption forms containing cannabis extracts must however involve a decarboxylation step to produce the active neutral forms. Many traditional methods of extracting inactive cannabinoids from raw cannabis biomass require subjecting the biomass to a heating process to decarboxylate the cannabinoids prior to extraction [13]. While it is relatively straightforward to heat dried cannabis for decarboxylation at particular temperature for specific time, in small quantities (kg or tens of kg), it becomes increasingly more difficult to carry it out if multiple tonnes of cannabis biomass must be subjected to decarboxylation prior to entering the extraction process. In addition, subjecting the biomass to a heating process may cause combustion, modification of the plant profile, negative effect on terpenes, or cause other undesirable effects that could lower quality or purity of the cannabis extract. For example, the process of decarboxylation of cannabis biomass can increase the number of cannabinoids occurring as artefacts by oxidative degradation or isomerization. Further, extraction of cannabis biomass that has been subjected to a thermal decarboxylation can lead to loss of valuable compounds including terpenes. Still further, decarboxylation of cannabis biomass prior to extraction does not provide an ability to control the amount of decarboxylation reaction to a desired percentage of neutral cannabinoids and so provide extract products with varying ratios of cannabinoid acids and corresponding neutral cannabinoids. So, any method of extraction that requires the cannabis biomass to be decarboxylated prior to extraction will hamper quality and purity of the cannabis extract.

In some extraction methods, many of the plant lipids and heavy waxes are co-extracted with the cannabinoids and other desirable components. As these are generally undesirable, they must be subsequently removed in the downstream process of winterization. Winterization involves dissolving the extract in alcohol, keeping it at sub-zero temperatures for a prolonged period to precipitate the heavy lipids, removing them by filtration and subsequently evaporating off all the alcohol to obtain the desired extract. This process is lengthy and usually costly and can result in loss of overall efficiency, *i.e.* loss of valuable cannabinoids. Similarly, if excessive chlorophyll or other pigmentation is extracted, this must be removed by a decolorization step (*e.g.*, treatment with activated carbon), which can again lead to loss of efficiency. Any extraction method that eliminates the need for these steps is desirable

3. **Scale-up Considerations and Cannabis Commercial Extraction Methods**

Extraction is the first step to separate the desired natural compounds from the raw biomass materials. Conventional extraction methods that have been applied to various natural products for many years include solvent extraction, distillation, mechanical pressing, and sublimation according to the extraction principle. Solvent extraction is the most widely used method. The extraction of biomass generally proceeds via the following stages: *(i)* the solvent is mixed with the solid biomass; *(ii)* the system is heated to the desired temperature, if needed *(iii)* the solvent diffuses into the solid particles; *(iv)* solute diffuses out of the solid biomass and dissolves in the liquid solvent; *(v)* the solvent is removed to provide the extracted solutes separated from the spent biomass. Any factor enhancing the diffusivity and solubility in the above steps will facilitate the extraction. The properties of the extraction solvent, the particle size of the raw materials, the solvent-to-solid ratio, the extraction temperature, and the extraction duration will affect the extraction efficiency and extraction selectivity.

The scale-up of an extraction process is not simply a case of using a larger reaction vessel – many factors need to be considered just to keep biomass and solvent contained, let alone achieve successful scale-up. Factors such as chemical and physical safety, availability of chemicals, analytical, chemical and engineering aspects, commercial considerations (cost and time), environmental and legal demands, etc. are just a few of the important initial factors that need to be taken into account for the scale-up.

In addition to biomass availability and specification changes underlined above, almost without exception, solvent will be the largest single component in any liquid-solid extraction. This raises several possibilities and challenges. While increasing relative solvent volume may increase extraction rates by increasing driving forces for diffusion, *i.e.* relative concentration gradients of solutes, reducing the solvent volume will reduce the time and energy required for engineering unit operations such as heating, cooling and removal of solvent by distillation, and reduce solvent recycling time or waste disposal volume. All these changes are beneficial on larger scale for which time, energy and waste disposal costs become significant due to the increased volumes involved. Environmental concerns and increasing regulation mean that fewer solvents are available for use, and restrictions are getting tighter. Therefore, the selection of the solvent is crucial for the extraction scale-up. Selectivity, solubility, cost, and safety should be considered in selection of solvents. Based on the law of similarity and intermiscibility (like dissolves like), solvents with a polarity value near to the polarity of the solute are likely to perform better and vice versa. In general, GRAS (Generally Recognized As Safe) solvents like ethanol and mixtures of water-ethanol are universal solvents for biomass extraction.

While there are various solvent methods for extracting the active compounds out of biomass, e.g., supercritical fluid extraction (SFE), Soxhlet, percolation, agitated tank, countercurrent, etc. [14-16], when considering cannabis extraction, none of these is optimal in all aspects. Molecules extracted through these processes may differ in the quality (physiochemical properties) and quantity hence altering the chemical composition of the extract; in addition, many of these methods have limitations when it comes to scaling up to suit mass production. Thus, it is very important to search for environmental-friendly and safer techniques and solvents allowing to obtain better quality and quantity of a cannabis extract from a given biomass, as well as maintaining the consistency in the cannabinoid profile of the extracts.

4. **Available Methods Currently Used for Commercial Cannabis Extraction**

There are generally three typical extraction methods currently being used for commercial cannabis extraction, albeit at only modest scale:

- Supercritical CO_2 (SC-CO_2) extraction
- Pressurized gas (hydrocarbon) extraction
- Conventional ethanol solvent extraction

These are discussed in more detail below.

In addition to these “big three”, there are several non-conventional, alternative extraction methods that have been applied to cannabis extraction, including for example ultrasound-assisted extraction,

Peer-reviewed version available at *Technologies* **2020**, *8*, 45; doi:10.3390/technologies8030045

hydrodynamic extraction and instant-controlled pressure drop extraction. Given that none of these have yet been demonstrated at any reasonable commercial scale, they are not further discussed.

4.1. Supercritical CO2 (SC-CO2) Extraction

Supercritical fluids are a well-documented alternative to traditional organic solvents suitable for various extractions. Any material s in its critical state when it is both heated above its critical temperature (T_c) and pressurized above its critical pressure (P_c) and hence there are no distinct liquid and gas phases. The specificity of this technique relies on solvent's physicochemical properties, which can be 'tuned' by an increase of pressure and/or temperature beyond its critical values [17-21].

Supercritical CO_2 extraction is a very common technique for cannabis extraction-separation, which uses supercritical CO_2 (74 bar, 31 ^{0}C) in a batch process. Although non-toxic and non-flammable, SC-CO_2 is, however, dangerous and requires very high pressures to be employed. In addition, the method is somehow inefficient and, therefore, not conducive to high throughputs, as well as environmentally damaging (*e.g.*, producing large amounts of the greenhouse gas carbon dioxide as a by-product). The resulting extracts are, however, considered to be solvent-free.

Another major drawback of SC-CO_2 extraction for cannabis is that decarboxylation must be carried out on the cannabis biomass upstream the extraction process (acidic cannabinoids are poorly soluble in SC-CO_2). This increases overall costs (decarboxylation must be performed in advance on what may be large quantities of cannabis biomass) and leads to the loss of some light volatile terpenes. SC-CO_2 also co-extracts heavy fats and waxes which must be subsequently removed in downstream processing steps (winterization), leading to further cannabinoid losses and reduction in overall efficiency or recovery of available cannabinoids. Finally, the scale up of SC-CO_2 is only possible by addition of multiple machines. This results in large capital costs and increased QA/QC costs when going to mass production scales.

4.2. Pressurized gas (hydrocarbon) extraction

Hydrocarbon extraction is the most popular technique that uses liquified gases such as n-propane and n-butane pressurized into liquids (2-10 bar) as solvents for extraction of cannabinoids. An advantage of the method is the possibility of these gases to remain in liquid phase at low pressure and the possibility to remove them from the system at the end of the extraction by gentle heating leading to an extract with low traces of residual solvent. Hydrocarbons such as n-butane and n-propane are good solvents for the low-polarity cannabinoids [17,22,23]. In this method, butane or propane is pressurized to a liquid state for extraction and then either depressurized or heated for removal from the obtained extracts. This extraction process is carried out in batch and creates what are known as cannabis "concentrates", *e.g.*, shatter, a viscous material with very high concentration of THC and other cannabis compounds like terpenes, which is popular for recreational users. Decarboxylation can be carried out upstream or downstream of the extraction. Although effective, the process is undesirable for medicinal and consumer products, due to the risk of solvent contamination. Safety is also a major concern given the high flammability/explosivity of the hydrocarbon solvents employed. In principle, the scale-up is only possible by the addition of multiple machines.

4.3. Conventional Ethanol Extraction

Peer-reviewed version available at *Technologies* **2020**, *8*, 45; doi:10.3390/technologies8030045

This extraction method is perhaps the most efficient method for capturing cannabinoids in either batch or continuous flow processing. Ethanol extraction can use decarboxylated biomass or decarboxylation can be performed on the extracted product. The main drawbacks of the method are linked to the high input ratios of biomass-ethanol and implicitly to the high quantities of solvent to be separated from the extract and recycled and also to the co-extracted molecules, such as fats, waxes, and pigments, which means more complex downstream processing (separation, purification, etc.).

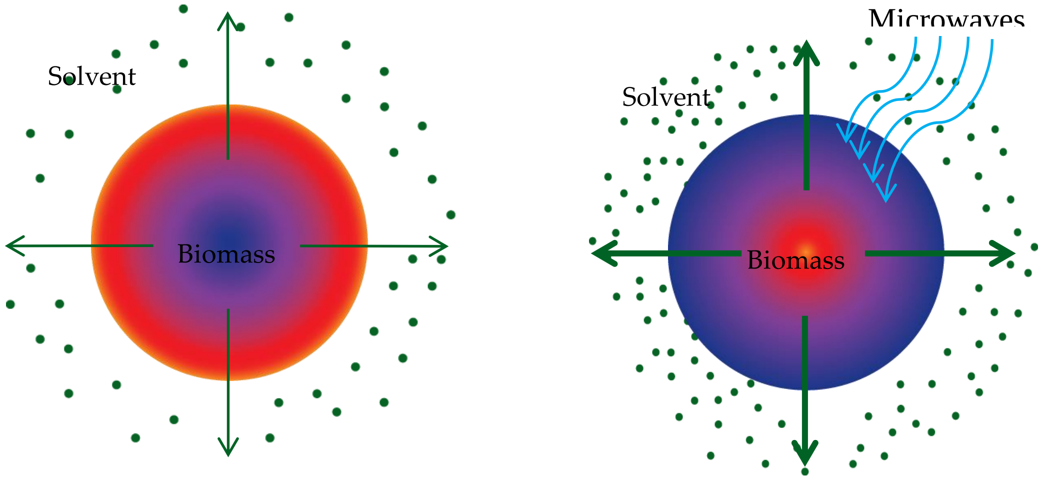
4.4. Microwave-Assisted Extraction

Microwave-assisted extraction (MAE) is different from the methods presented above because the extraction occurs as a result of the volumetric heating as opposed to transferring heat from the surface inwards, making the process more efficient and more uniform due to the ability to precisely control temperature and contact time.

The field of MAE of natural compounds is quite young. In the last two decades, new investigations have been prompted by an increasing demand of more efficient extraction techniques, amenable to automation; shorter extraction times, reduced organic solvent consumption, energy and costs saved, were the main tasks pursued. Driven by these goals, advances in microwave extraction have resulted in a number of innovative techniques such as microwave assisted solvent extraction, vacuum microwave hydro-distillation, microwave Soxhlet extraction, microwave-assisted Clevenger distillation, compressed air microwave distillation, microwave headspace extraction, microwave hydro-diffusion and gravity, and solvent-free microwave extraction [14,15,17,13]. One of the success stories of the 21st Century has been the partial replacement of conventional extraction processes, with *green* procedures (reducing energy, time, solvent, and waste) based on microwave irradiation [24].

The fundamentals of the microwave-assisted extraction process are different from those of conventional solvent extraction methods (solid–liquid or simply extraction) because the extraction can occur as the result of changes in the cell structure caused by electromagnetic waves, Figure 3, Table 1. Even if cell structure is unchanged, the instant volumetric heating possible with microwaves as opposed to transferring heat from the surface, inwards, is more efficient, uniform and less prone to overkill. Controllability is by far the greatest advantage of microwaves over conventional thermal technologies. In processing applications, the ability to instantaneously apply and turn off the heat source as desired makes enormous difference to the product quality and hence the production economics. The very nature of heating through the involvement of the raw material under processing (instead of using fossil fuels or less efficient, indirect electrical heating systems) brings about quality consistency as well as positive environmental impacts [25,26].

An important element of MAE is that the driving force for extraction is not limited to the process of diffusion. Conventional solid-liquid extraction involves soaking, washing or contacting the solid material with usually hot (50°C to 80°C) solvent to extract the target compounds and normally two or three extractions are needed, increasing the solvent and energy usage. Moreover, extraction occurs by diffusion, meaning that the only driving force for the process is the concentration gradient of the product between the biomass and the solvent. With MAE the solvent requirement is lesser as compared to coventional methods and material is exhausted with one extraction only. Moreover the microwave energy can be directed directly to and selectively absorbed by the water (free or bound water) if water present in the biomass. This creates a very rapid temperature increase within the biomass cells, leading to pressure build-up and forcing the bioactives out into the surrounding solvent by a pressure-enhanced mass transfer. This mass transfer may be further enhanced by the fact that the thermal gradient is in the same direction as the mass transfer – Figure 3.



Conventional extraction
Diffusion-driven process - relies
on concentration gradients

Microwave-assisted extraction
Instant in-core heating creating a
pressure-driven process leading to increased
mass and heat transfer rates among the
reaction products

Figure 3. Biomass-solvent extraction: Conventional vs. Microwaves

Table 1. Solvent-biomass extraction: Conventional vs. Microwaves

CONVENTIONAL EXTRACTION	MICROWAVE ASSISTED EXTRACTION
Mechanism via diffusion	Pressure-enhanced mass transfer
Concentration gradient of actives between the biomass and the solvent is the driving force	**Microwave energy** is selectively absorbed by the residual water present in the biomass cells
Diffusion is **slow**, particularly as the actives become more concentrated in the solvent	Results in **rapid** pressure buildup within cells leading to a pressure-driven mass transfer of actives (pop-corn effect)
Eventually reaches a **saturation point**	**Extraction is very fast and not limited** by an equilibrium state – transfer continues as long as energy is applied
Requires **high solvent** ratios and **multiple extraction** stages to achieve reasonable recovery of actives	Results in short extraction times, **reduced solvent** requirements and **fewer extraction** stages

The basics of the MAP™[1] continuous flow microwave-assisted extraction of cannabis consists of coupling microwave heating and continuous flow technology and as such creating a very promising way to produce high value-added extracts since unlike batch processing, the continuous flow has been demonstrated to facilitate process intensification and contributes to a safe, efficient and sustainable production. By employing continuous-flow microwave-assisted extraction, it is possible to control extraction time and temperature very precisely, both of which can greatly influence extraction efficiency and the composition of the extract.

A schematic of one process involved in the extraction of the cannabis biomass and decarboxylation of the extracted products is presented in Figure 4 while results are listed in Table 2[2]. In this method, the raw milled cannabis biomass is mixed with a solvent (*e.g.*, ethanol, IPA, pentane, PEG400) selected based on its dielectric and parameter properties vs. type of biomass & its concentration of cannabinoids. The obtained slurry is pumped in the continuous flow microwave-assisted extraction reactor and progressively heated to the desired extraction temperature by using 915 MHz microwaves – Figure 5 [26]; the microwave density can be automatically 'tuned' to the process conditions as to reach densities between 0.1 and 10 kW/kg of biomass. Downstream the extractor, the spent biomass and the extract are separated from the slurry. The extract is treated to obtain a final product containing the target compounds in sufficiently high yield and high purity. The spent biomass may be processed to yield less than 0.3% concentration of THC naturally produced by plants and disposed of once this condition has been achieved.

Table 2. Results of industrial scale cannabinoid extraction runs from cannabisbiomass; biomass flow 30kg/h, solvent flow 360L/h.

Run	Mass of biomass, kg	Purity of cannabis extract, THC%	THC recovery in the extract, %
1	100	61.4	92.6
2	100	55.1	93.4

The microwave-assisted extractor consists of a food grade stainless steel tube within which a mechanical stirrer is placed. Microwaves are provided from a 75 kW (max. power), 915 MHz microwave generator consisting of a low ripple switch mode power supply, a magnetron head and a circulator + water cooled load with reflected power meter. The microwave generator can be operated from 2-3 kW up to 75 kW in continuous wave (CW) mode or controlled pulse. Due to the possibility of working with flammable solvents, the microwave generator is installed in a different (non-ATEX) room. The microwave transmission line, standard WR975 rectangular waveguide, passes the wall between the ATEX and non-ATEX environments through a separation window and then it splits into two inlets delivering equal microwave power all along the reactor. In the extractor the separation between the reaction mixture and the microwave distribution line is done via microwave transparent windows. Due to the continuous measuring and controlling of the reflected power and

---

[1] MAP™ is a patented microwave-asssited processing by Radient Technologies Inc. (www.radientinc.com), which has been successfully operating a continuous-flow microwave extractor in Canada for over five years at throughputs over 200 kg/h of biomass input.

[2] Due to the commercial sensitivity of the subject, the disclosure of the results is limited to two examples without the full disclosure of the operational conditions of the extraction.

Peer-reviewed version available at *Technologies* **2020**, *8*, 45; doi:10.3390/technologies8030045

the automatic impedance tuner installed immediately after the circulator (in the non-ATEX zone), the microwave forward power is automatically adjusted as to maximize the absorbed energy by the extraction mixture and to minimize energy losses by reflected power. Microwave components located within the ATEX zone are continuously purged with nitrogen; arc detectors are installed within all microwaves components as such as the microwaves are shut down as soon as arcing detected. Wall mounted microwave leakage detectors can shut down the microwaves if leakage levels ≥ 2.3 mW/cm² are detected around the reactor.

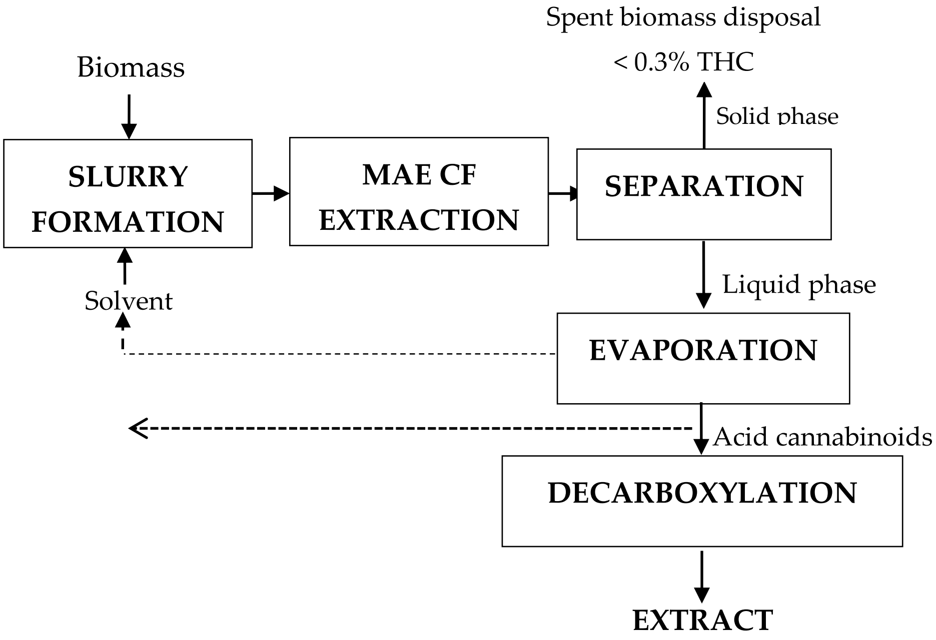


Figure 4. Schematic of the microwave-assisted cannabis extraction & acidic cannabinoids decarboxylation

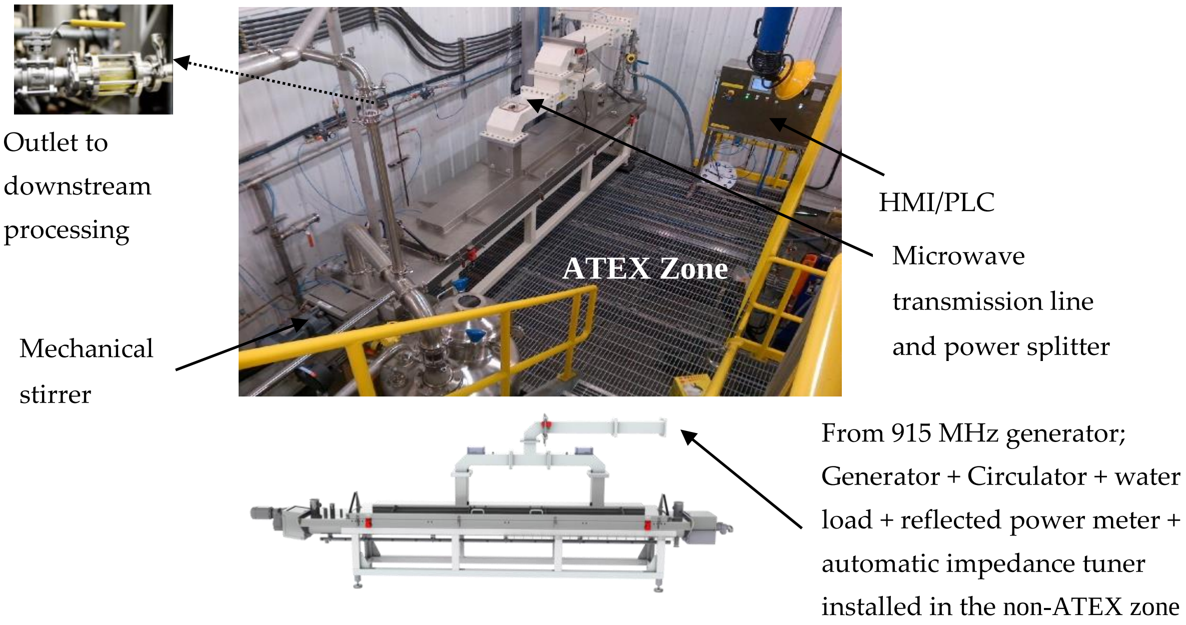


Figure 5. Photo and schematics of the continuous flow microwave extractor in ATEX environment; microwave generator not shown

As described in Figures 4 and 5, the main advantages of the microwave-extraction related to cannabis biomass are:

- Continuous-flow method at atmospheric pressure which allows for much higher volumes of cannabis biomass to be processed in much less time than existing extraction methods;
- Achieved higher rates of consistency and quality because the process does not require stopping and restarting material flows;
- Scale-up to industrial scale without the need to purchase an endless supply of new machinery and without the use of pressurised batch vessels;
- Eliminates additional steps required in most extraction methods, such as biomass decarboxylation and winterisation;
- Ability to achieve high extraction efficiency at industrial scale. Typical recovery of active compounds using supercritical CO_2 remains around 70-80%, via microwave-assisted up to 95% of the active compounds (Table 1) from cannabis biomass can be recovered.

From a process intensification view, the continuous flow extraction and its heating via microwaves comes with several additional benefits, including significantly increased flexibility and safety with respect to operation:

- The contact time between the biomass and solvent before, during and after microwave treatment can be adjusted much more easily;
- It is possible to precisely control biomass residence time in the microwave zone and - if desired - separate the biomass from the solvent very quickly after treatment, or continue contact for any length of time at any temperature, depending on the desired outcome;
- The use of multiple microwave field deposition points through the use of a split waveguide and a "ridge wave deposition" allowing for non-uniform dispersal of the wave from the inlet to the outlet to account for changing dielectric properties as the material is treated;
- It has an automatic impedance matching unit that allows for constant, automatic adjustment of the field strength and microwave energy absorption maximization;
- It has a built-in mechanical agitator with variable speed control to randomize movement of biomass thus making the field uniform for the materials at all times;
- It is fully-automated (operators simply input desired MW parameters on an HMI and it runs itself while connected to the plant PLC systems);
- It is fully "ATEX" or "Hazardous zone" classified, meaning it can be used with any flammable liquid and be completely safe.

The extractor is also easily scalable. The continuous flow approach eliminates the requirement for having geometric similarity between scales, *i.e.* the equipment shape and dimensions do not have to scale proportionately. Classically, even geometric similarity does not ensure thermal similarity in scaled systems; for example, heat transfer is an interface-controlled process and so the surface area relative to the volume is critical. As the volumetric scale increases, the area relative to the volume decreases and the overall efficiency of heat transfer can decline considerably. There is no thermal inertia with microwaves, on the other hand. Since penetration depth is not an issue with the continuous flow design, the energy is deposited uniformly throughout the mixture resulting in rapid energy transfer and direct dielectric heating – hence the thermal inertia inherent to classical methods is not an issue.

5. Conclusions

As a result of increased legislation, concerns about the environment and competition within the globalized market, it has become paramount to look for and implement innovative, clean and sustainable ways to obtain natural extracts, *i.e.* green extraction of natural products. Green extraction refers to looking for, designing and implementing extraction processes that lead to (*i*) a reduction in energy consumption, (*ii*) utilization of alternative solvents to obtain products that are natural and renewable, and (*iii*) extracts that are safe and of high quality.

As the cannabis industry grows, so will the equipment options for extraction. These advances will probably go across the kinds of extraction processes, and the connection between extraction and analytical testing could also see improvement. Even with the best equipment, though, only skilled operators can produce the intended results. So, training operators as needed should always be performed in any company to guarantee results. In addition to it, there is a necessity to explore new reactor concepts by emphasising on dedicated designs that assure controllability and monitoring of the process conditions.

Microwave continuous flow extraction is a good example of process intensification. In this reactor, the process is run in a continuously flowing stream, enabling very tight process control and improved mass heat and mass transfer, consequently achieving higher extraction control and higher product quality. Furthermore, continuous extractors can be easily scaled up by placing multiple cavities in series or in parallel, thereby shortening development time for full scale production.

Author Contributions:
Dr. Marilena Radoiu: writing – original draft preparation; design of the microwave equipment, laboratory and commercial scale;
Dr. Harmandeep Kaur: writing – review and editing, feasibility studies, process development, scale up and technology transfer at industrial scale;
Dr. Anna Bakowska-Barczak: writing – review and editing, conducted initial experiments;
Dr. Steven Splinter: writing – review and editing, supervision of laboratory and industrial scale testing, project administration, intellectual property.
All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Wikipedia, Available online: https://en.wikipedia.org/wiki/Cannabis (accessed on 7th April 2020).
2. Joy, J.E.; Watson, S.J. Jr.; Benson, J.A. Jr. The Medical Value of Marijuana and Related Substances. In *Marijuana and Medicine: Assessing the Science Base*. Consensus Study Report. National Academies Press: Washington DC, USA, 1999. Available online: https://www.nap.edu/catalog/6376/marijuana-and-medicine-assessing-the-science-base (accessed on 29th June 2020), doi: 10.17226/6376.
3. EMCDDA, Medical use of cannabis and cannabinoids, Questions and Answers for Policymaking, 2018. Available online: http://www.emcdda. europa.eu (accessed 10th May 2020), doi:10.2810/979004.
4. The Health Effects of Cannabis and Cannabinoids: The Current State of Evidence and Recommendations for Research. National Academies of Sciences, Engineering, and Medicine; Health and Medicine Division; Board on Population Health and Public Health Practice; Committee on the

Peer-reviewed version available at *Technologies* **2020**, *8*, 45; doi:10.3390/technologies8030045

Health Effects of Marijuana: An Evidence Review and Research Agenda. Washington (DC): National Academies Press (US). Available online: https://www.ncbi.nlm.nih.gov/books/NBK423845/ (accessed on 27th June 2020), doi: 10.17226/24625.

5. EMCDDA Insights, An overview of cannabis potency in Europe, 2004. Available online: http://www.emcdda. europa.eu (accessed on 10th May 2020).
6. Hanus, L.O.; Meyer, S.M.; Munoz, E.; Taglialatela-Scafati, O.; Appendino, G. Phytocannabinoids: a unified critical inventory. *Nat. Prod. Rep*. **2016**, *33*, 1357-1392.
7. Bindesri, S.D.; Jebailey, R.; Albarghouthi, N.; Pye, C.C.; Brosseau, C.L. Spectroelectrochemical and computational studies of tetrahydrocannabinol (THC) and carboxy-tetrahydrocannabinol (THC-COOH). *Analyst* **2020**, *145*, 1849-1857.
8. Gazendam, A.; Nucci, N.; Gouveia, K.; Khalik, H.A.; Rubinger, L.; Johal, H. Cannabinoids in the Management of Acute Pain: A Systematic Review and Meta-analysis, *Cannabis and Cannabinoid Research*. *Ahead of print*. Available online: https://www.liebertpub.com/doi/10.1089/can.2019.0079 (accessed on 9th April 2020).
9. Truta, E.; Gille, E.; Toth, E.; Maniu, M. Biochemical Differences in Cannabis Sativa L. Depending on Sexual Phenotype, *J Appl Genet*. **2002**, *43*, 451–462.
10. Nahler, G.; Jones, T.M. Pure cannabidiol versus cannabidiol-containing extracts: distinctly different multi-target modulators, *J. of Alternative, Complementary and Integrative Medicine* **2018**, *4*, 262-271.
11. Villena, K. Cannabis in beauty and personal care: prospects, opportunities and challenges, Passport, *Euromonitor International*, November 2019.
12. Smith, D.; Bloor, R.; George, C.; Pysanenko, A.; Spanel, P. Release of toxic ammonia and volatile organic compounds by heated cannabis and their relation to tetrahydrocannabinol content, *Anal. Methods* **2015**, 7, 4104-4110.
13. Wang, M.; Wang, Y-H.; Avula, B.; Radwan, M.M.; Wanas, A.S.; van Antwerp, J.; Parcher, J.F.; El Sohly, M.A.; Khan, I.A. Decarboxylation study of acidic cannabinoids, *Cannabis Cannabinoid Res*. **2016,** *1*, 262–271.
14. Belwal, T.; Ezzat, S.M.; Rastrelli, L.; Bhatt, I.D.; Daglia, M.; Baldi, A.; Devkota, H.P.; Orhan, I.E.; Patra, J.K.; Das, G.; Anandharamakrishnan, C.; Gomez-Gomez, L.; Nabavi, S.F.; Nabavi, S.M.; Atanasov, A. A critical analysis of extraction techniques used for botanicals: Trends, priorities, industrial uses and optimization strategies *Trends in Analytical Chemistry* **2018,** *100*, 82-102. https://doi.org/10.1016/j.trac.2017.12.018
15. Perino-Issartier, S.; Maingonnat, J-F.; Chemat, F. Microwave Food Processing. In *RSC Green Chemistry No. 10. Alternatives to Conventional Food Processing*, Proctor, A., Ed.; The Royal Society of Chemistry: London, UK, 2011, pp. 415 – 458, doi.org/10.1039/9781849730976
16. Zhou, L.; Lie, Y.; Briers, H.; Fan, J.; Remon, J.; Nystrom, J.; Budarin, V.; Macquarrie, D.; McElroy, C.R. Natural Product Recovery from Bilberry (Vaccinium myrtillus L.) Presscake via Microwave Hydrolysis. *ACS Sustainable Chem Eng*. **2018**, *6*, 3676-3685. doi.org/10.1021/acssuschemeng.7b03999.
17. Chemat, F.; Abert Vian, M.; Fabiano-Tixier, A-S.; Nutrizio, M.; Rezet Jambrak, A.; Munetaka, P.E.S.; Lorenzo, J.M.; Barba, F.J.; Binello, A.; Cravotto, G. A review of sustainable and intensified techniques for extraction of food and natural products. *Green Chemistry* **2020**, open access www.rsc.com, downloaded 02nd April 2020.

18. King, J.K.; Srinivas, K.; Zhang, D. Advances in Critical Fluid Processing. In *RSC Green Chemistry No. 10. Alternatives to Conventional Food Processing*, Proctor, A., Ed.; The Royal Society of Chemistry: London, UK, 2011, pp. 93-144. https://doi.org/10.1039/9781849730976-00093.
19. Ribeiro Grijó, D.; Vieitez Osorio, I.A. ; Cardozo-Filho, L. Supercritical extraction strategies using CO2 and ethanol to obtain cannabinoid compounds from Cannabis hybrid flowers. *J. of CO_2 Utilization* **2018**, *28*, 174-180. doi: 10.1016/j.jcou.2018.09.022
20. Attard, T.M.; Hunt, A.J. Supercritical Carbon Dioxide Extraction of Lipophilic Molecules, In *Green Chemistry Series No. 57, Supercritical and Other High-pressure Solvent Systems: For Extraction, Reaction and Material Processing*, Hunt, A.J., Attard, T.M. Eds.; The Royal Society of Chemistry: London, UK, 2018, pp. 40-76. https://doi.org/10.1039/9781788013543-00040
21. Rovetto, L.J.; Aieta, N.V. Supercritical carbon dioxide extraction of cannabinoids from Cannabis sativa L. J. of Supercritical Fluids 2017, 129, 16-27. doi: 10.1016/j.supflu.2017.03.014
22. Moreno, T.; Montanes, F.; Tallon, S.J.; Fenton, T.; King, J.W. Extraction of cannabinoids from hemp (*Cannabis sativa* L.) using high pressure solvents: an overview of different processing options. *J. Supercrit. Fluids* **2020**, *161*, 104850. doi: 10.1016/j.supflu.2020.104850
23. Gallo-Molina, A.C.; Castro-Vargas, H.I.; Garzón-Méndez, W.F.; Martínez Ramírez, J.A.; Rivera Monroy, Z.J.; King, J.W.; Parada-Alfonso, F. Extraction, isolation and purification of tetrahydrocannabinol from the *Cannabis sativa* L. plant using supercritical fluid extraction and solid phase extraction. *J. of Supercritical Fluids* **2019**, *146*, 208-216. doi: 10.1016/j.supflu.2019.01.020
24. Anastas, P.; Eghbali, N. Green Chemistry: Principles and Practice. *Chem. Soc. Rev.* **2010**, *39*, 301–312. doi: 10.1039/B918763B
25. Patrascu, M.; Radoiu, M. Rose Essential Oil Extraction from Fresh Petals Using Synergetic Microwave & Ultrasound Energy: Chemical Composition and Antioxidant Activity Assessment. *J. Chem. Eng.* **2016**, *10*, 136-142, doi: 10.17265/1934-7375.
26. Radoiu, M.; Splinter, S.; Popek, T. Continuous industrial-scale microwave-assisted extraction of high-value ingredients from natural biomass. Proceedings of the 53rd IMPI’s Microwave Power Symposium., Las Vegas, NV, USA, 18-20 June 2019.