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Advancements and challenges in green extraction techniques for Indonesian natural products: A review

Nicky Rahmana Putra [a,b], Yustisia Yustisia [a], R. Bambang Heryanto [a], Asmaliyah Asmaliyah [a], Miswarti Miswarti [a], Dwila Nur Rizkiyah [b], Mohd Azizi Che Yunus [b], Irianto Irianto [c], Lailatul Qomariyah [d,*], Gus Ali Nur Rohman [e]

[a] National Research and Innovation Agency, Indonesia
[b] Centre of Lipid Engineering and Applied Research (CLEAR), Ibnu Sina Institute for Scientific and Industrial Research, Universiti Teknologi Malaysia, 81310, UTM Johor Bahru, Malaysia
[c] Department General Education, Faculty of Resilience, Rabdan Academy, Abu Dhabi, United Arab Emirates
[d] Department of Industrial Chemical Engineering, Institut Teknologi Sepuluh Nopember, 60111 Surabaya, Surabaya, Indonesia
[e] Centre of Research Excellence in Nanotechnology (CENT) Research Institute, King Fahd University of Petroleum & Minerals, Dhahran 34463, Saudi Arabia

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ABSTRACT

The paper examines the advancements and obstacles in environmentally sustainable extraction methods for natural products in Indonesia. It presents a comprehensive examination of conventional extraction methodologies utilized in Indonesia and analyses their inherent constraints and ecological ramifications. The subsequent section of the paper examines a range of environmentally friendly extraction methods, encompassing their underlying principles, advantages, disadvantages, and instances of their implementation in the context of Indonesia. Furthermore, the study examines the challenges and constraints associated with green extraction practices in Indonesia, encompassing technical and economic impediments and regulatory concerns. Furthermore, this study explores recent advancements in environmentally sustainable extraction methods for natural products in Indonesia and their potential practical uses. The review underscores the importance of implementing environmentally responsible and sustainable extraction practices in Indonesia and provides recommendations for further research and development in this area. The article offers significant perspectives on the condition of green extraction methods employed for Indonesian natural products and highlights potential pathways for future progress in this field.

1. Introduction

Green extraction techniques are a set of environmentally-friendly methods for extracting desired components from natural products such as plants, herbs, and fruits (Panja, 2018). These techniques aim to reduce the environmental impact associated with traditional extraction methods, which typically involve the use of solvents that can have negative effects on human health and the environment (Calderón-Oliver and Ponce-Alquicira, 2021; Chemat et al., 2020). Green extraction typically involve the use of non-toxic solvents, such as water or carbon dioxide, and/or physical methods such as microwave-assisted extraction, ultrasound-assisted extraction, or pressurized liquid extraction (Jha and Sit, 2022; Mustafa and Turner, 2011). These techniques can result in higher yields of target compounds, and reduced waste production compared to traditional extraction methods (Putra et al., 2023). Green extraction techniques have become increasingly important in recent years, particularly in the food, pharmaceutical, and cosmetic industries, where there is growing demand for natural products that are produced in a sustainable and environmentally responsible way (Rizkiyah et al., 2023).

Indonesia is well-known for its abundant natural resources and biodiversity, making it a significant source of natural products used for a variety of purposes for centuries (Henley, 2008; Sholikhah, 2016). Indonesian natural products include a variety of seasonings, botanicals, medicinal plants, and essential oils as shown in Table 1 (Zahara et al., 2018). These natural products have significant economic, cultural, and ecological importance. Indonesia is the world's largest producer of palm oil, a key constituent in numerous culinary products and a significant

* Corresponding author.
E-mail address: laila.qomariyah@its.ac.id (L. Qomariyah).

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Table 1
Example natural products in Indonesia.

Natural product	Source
Clove Oil	Clove tree (*Syzygium aromaticum*)
Patchouli Oil	Patchouli plant (*Pogostemon cablin*)
Nutmeg Oil	Nutmeg tree (*Myristica fragrans*)
Citronella Oil	Citronella plant (*Cymbopogon nardus)*
Ginger Oil	Ginger plant (*Zingiber officinale*)
Turmeric	Turmeric plant (*Curcuma longa*)
Cinnamon	Cinnamon tree (*Cinnamomum verum*)
Galangal	Galangal plant (*Alpinia galanga*)
Lemongrass Oil	Lemongrass plant (*Cymbopogon citratus*)
Camphor Oil	Camphor tree (*Cinnamomum camphora*)
Cananga Oil	Cananga tree (*Cananga odorata*)
Eucalyptus Oil	Eucalyptus tree (*Eucalyptus globulus*)
Sandalwood Oil	Sandalwood tree (*Santalum album*)
Betel Nut	Betel palm (*Areca catechu*)
Gambier	Gambier plant (*Uncaria gambir*)
Tamarind	Tamarind tree (*Tamarindus indica*)
Java Tea	Java tea plant (*Orthosiphon aristatus*)
Kaffir Lime	Kaffir lime tree (*Citrus hystrix*)
Pandan Leaf	Pandan plant (*Pandanus amaryllifolius*)
Coconut Oil	Coconut tree (*Cocos nucifera*)
Cocoa	Cocoa plant (*Theobroma cacao*)
Coffee	Coffee plant (*Coffea arabica*)
Black Pepper	Black pepper plant (*Piper nigrum*)
White Pepper	White pepper plant (*Piper nigrum*)
Red Ginger	Red ginger plant (*Zingiber officinale var. Rubrum*)
Temulawak	Temulawak plant (*Curcuma xanthorrhiza*)
Mangosteen	Mangosteen tree (*Garcinia mangostana*)
Rattan	Rattan palm (*Calamus spp.*)
Dragon Blood	Dragon Blood tree (*Daemonorops spp.*)
Gum Rosin	Pine tree (*Pinus spp.*)
Benzoin	Benzoin tree (*Styrax spp.*)
Cempaka	Cempaka tree (*Magnolia champaca*)
Jasmine	Jasmine plant (*Jasminum spp.*)
Frangipani	Frangipani tree (*Plumeria spp.*)
Kayu Putih Oil	Kayu Putih tree (*Melaleuca leucadendron*)
Kratom	Kratom tree (*Mitragyna speciosa*)
Jamu	Traditional herbal medicine made from various plants

Note: This table is not exhaustive and there are many other natural products found in Indonesia.

export commodity (Farobie and Hartulistiyoso, 2021). In addition, the nation is renowned for its spices, such as nutmeg, cinnamon, and cloves, which are extensively used in the culinary industry due to their distinctive flavours and fragrances (Chomchalow, 2001; Vázquez-Fresno et al., 2019). Medicinal plants from Indonesia, such as turmeric and ginger, are also well-known for their health benefits and have been used for centuries in traditional medicine (Sachan et al., 2018; Woerdenbag and Kayser, 2014). In Indonesia, the natural products industry provides employment opportunities and contributes significantly to the country's economy. Moreover, Indonesian natural products play a significant role in the country's culture and are integral components of traditional cuisine, medication, and cosmetics (Sen et al., 2011). Given the immense variety of natural products found in Indonesia, their sustainable use is essential for fostering the country's economic growth and conserving its abundant biodiversity.

In addition to their economic and cultural significance, natural products from Indonesia also have ecological importance (Mohri et al., 2013). The country's abundant biodiversity makes it a valuable source of potential drug prospects, functional foods, and other natural constituents for a variety of uses. The Indonesian natural products industry has the potential to promote conservation efforts by providing economic incentives for preserving natural ecosystems and promoting sustainable agricultural practices (Phelan et al., 2020). However, the extraction and processing of natural products can have negative environmental impacts; therefore, it is essential to implement sustainable extraction practices that minimize environmental damage while preserving the quality and quantity of extracted products (Kamaruddin et al., 2022; Tran et al., 2019). Consequently, the development of green extraction techniques for Indonesian natural products is of utmost importance, as they offer a more sustainable and environmentally conscious extraction method. In addition, the adoption of green extraction techniques can result in increased yields of target compounds, decreased waste production in comparison to conventional extraction methods (Chemat et al., 2020; Rizkiyah et al., 2023; Tiwari, 2015). Therefore, valorisation of Indonesian natural products play a vital role in the nation's economy, culture, and ecology, and their sustainable utilization is crucial for assuring the long-term health of the nation's people and environment. Fig. 1 shows the concept of valorisation of natural plants extract using green processes has emerged as a promising area of research for sustainable and environmentally friendly methods of extracting bioactive compounds.

The primary objective of a study on green extraction techniques for Indonesian natural products is to evaluate their yield, purity, and sustainability. The purpose of this study is to identify the challenges and limitations of green extraction techniques in Indonesia and to propose solutions to these problems. It also attempts to assess the commercial viability and scalability of green extraction techniques for Indonesian natural products that have been developed recently. The economic and environmental effects of various green extraction methods will be evaluated and contrasted to those of conventional extraction methods. The study's ultimate objective is to provide insights and recommendations for future research and development in the field of green extraction for Indonesian natural products, with the intention of promoting environmentally benign and sustainable extraction practices in the country extracted products.

2. Method of literature review

Literature data were obtained from databases such as science direct, SCOPUS. Google Scholar and web of science with keywords used for extracting and analyzing literature data.

3. Traditional extraction techniques in Indonesia

3.1. Overview of traditional extraction techniques used in Indonesia

Indonesia has a lengthy history of utilizing traditional extraction methods to acquire natural products (Hendra et al., 2011). In Indonesia, maceration, percolation, and distillation are some of the most common traditional extraction techniques (Tambun et al., 2021). To extract the desired compounds, maceration involves immersing plant material in a solvent, such as water or alcohol, for a period of time. Percolation, on the other hand, involves passing a solvent through a column containing plant material in order to progressively extract the compounds (Irfan et al., 2022). Distillation is a process in which plant material is heated to release volatile compounds, which are then collected as vapours and condensed back into a liquid state. In Indonesia, traditional extraction methods have been used for centuries and are still extensively employed, particularly in small-scale operations (Singh, 2017). However, traditional extraction techniques have limitations, such as low yields and the use of significant quantities of solvents, which can have detrimental environmental effects (Mercer and Armenta, 2011). In addition, heat-sensitive compounds can degrade during high-temperature extraction procedures, resulting in the loss of some valuable compounds (Ochoa et al., 2020; Ranitha et al., 2014). To address these limitations, alternative extraction methods that are more efficient, sustainable, and environmentally favourable are required.

Another limitation of traditional extraction techniques used in Indonesia is that they may not be suitable for extracting specific types of compounds (Easmin et al., 2015). For example, some compounds may not be soluble in the solvents used in traditional extraction methods or may be too large to be extracted efficiently. Additionally, traditional extraction methods may not be effective at separating compounds with similar chemical properties, leading to impure extracts (Gupta et al.,

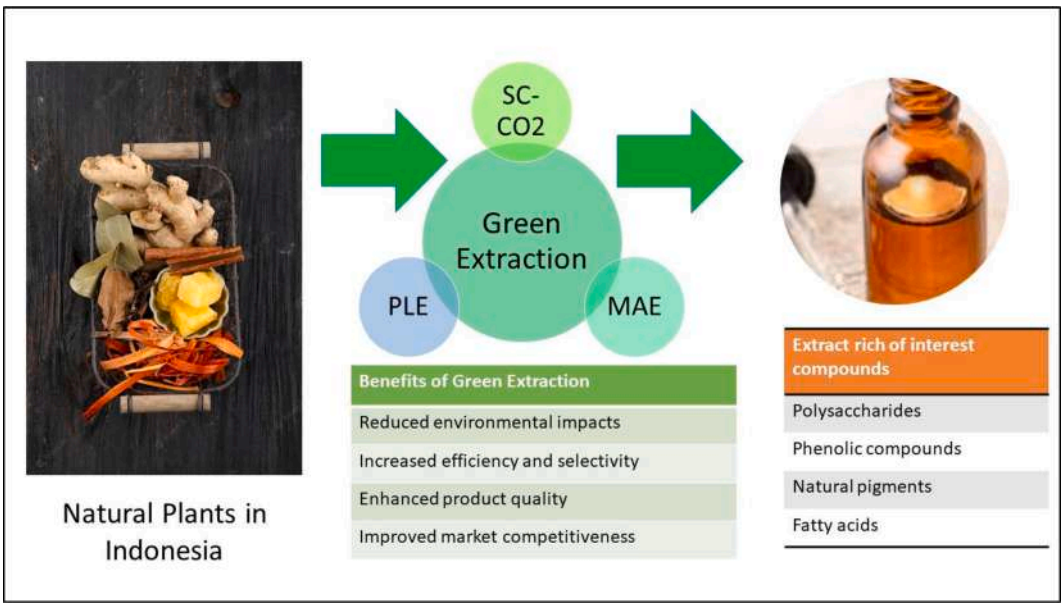

Fig. 1. Concept of valorisation of natural plants extract using green processes.

2012). To overcome these limitations, modern extraction techniques have been developed that use alternative solvents or extraction methods, such as supercritical fluid extraction, microwave-assisted extraction, and ultrasound-assisted extraction (Daud et al., 2022). These techniques have been shown to be more efficient and selective, resulting in higher yields of pure compounds while using fewer solvents and reducing environmental impact (Putra et al., 2022). However, the use of modern extraction techniques may require specialized equipment and training, which can increase the cost and complexity of the extraction process. On the other hand, traditional extraction techniques used in Indonesia have played an important role in the country's natural products industry, but their limitations and potential negative environmental impacts make it important to explore and develop more sustainable and efficient extraction techniques.

3.2. *Limitations and challenges of traditional techniques*

Traditional extraction techniques in Indonesia have several of limitations and challenges that can compromise their effectiveness and viability. The use of significant quantities of solvents, which can be expensive and have negative environmental effects, is one of the greatest obstacles (Clark, 1999; Goh et al., 2019). Traditional extraction techniques employ solvents that can be hazardous to human health and the environment. The degradation of heat-sensitive compounds during high-temperature extraction procedures can also result in the loss of some valuable compounds during the extraction process (Phong et al., 2022). The low yields of some traditional extraction methods can also be problematic, as they can lead to decreased profitability for producers and increased prices for consumers.

In addition to the aforementioned challenges and limitations, traditional extraction techniques in Indonesia may also be subject to standardization and quality control issues. Traditional extraction methods rely on the expertise and experience of the extractor to determine the optimal extraction conditions, which can lead to variation in the quality and composition of the extracts. This can make it difficult to guarantee the purity and potency of natural products extracted using conventional methods. Due to the size and capacity limitations of the apparatus employed, traditional extraction methods may not be appropriate for large-scale production. This can hinder the capacity of traditional extraction methods to satisfy the increasing demand for natural products in Indonesia and around the world.

Concerns regarding deforestation, habitat devastation, and loss of biodiversity may render the use of traditional extraction techniques unsustainable over the long term (Magoro et al., 2010). The overuse of traditional extraction methods can also result in the overharvesting of certain plant species, leading to the depletion of natural resources and the potential for negative effects on local ecosystems and communities. In general, the limitations and difficulties of traditional extraction methods highlight the need for the development of more sustainable, efficient, and standardized extraction methods that can produce high-quality natural products while minimizing negative environmental impacts and promoting social and economic sustainability. The inability to extricate specific compounds selectively is an additional drawback of conventional extraction methods. Compounds with comparable chemical properties may not be effectively separated using conventional techniques, resulting in impure extracts. This may result in extracts of inferior quality that are unsuitable for specific applications, such as pharmaceutical or cosmetic products.

An illustrative instance of deforestation in Indonesia pertains to the deliberate removal of rainforests to establish palm oil plantations. Indonesia is globally recognized as a prominent contributor to the palm oil industry, occupying a significant position as one of the largest producers worldwide. The versatile application of palm oil extends to various sectors, encompassing food production, cosmetics manufacturing, and the production of biofuels. The increasing global demand for palm oil has resulted in extensive deforestation of rainforest regions, specifically in Sumatra and Borneo (Kalimantan), to accommodate the establishment of palm oil plantations. The practice of land clearance for palm oil plantations frequently employs slash-and-burn methods, whereby extensive forested regions are intentionally ignited to expedite land clearance. Nevertheless, this particular activity results in the substantial emission of carbon dioxide and various other greenhouse gases into the Earth's atmosphere, thereby making a significant contribution to the phenomenon of global climate change. The proliferation of palm oil plantations has resulted in significant ramifications for biodiversity. Indonesia harbors a wide array of distinct and varied flora and fauna, encompassing critically endangered species such as the Sumatran orangutan, Sumatran tiger, and Bornean pygmy elephant. The potential for extinction looms over these species as their native habitats are progressively destroyed. In addition, the process of deforestation undertaken to establish palm oil plantations has resulted in the deprivation of livelihoods and the forced relocation of indigenous

communities that have resided in these regions for multiple generations. These communities frequently exhibit robust cultural connections to the forests and depend on them for their customary way of life and sustenance. There is a concerted endeavor underway to tackle the problem of deforestation in Indonesia. This involves certain companies pledging to adopt more sustainable practices in the production of palm oil, as well as the Indonesian government enacting policies pertaining to green technology. These measures aim to safeguard forests and encourage the adoption of sustainable land utilization practices. Nevertheless, a significant obstacle persists in finding a harmonious equilibrium between the pursuit of economic progress and the imperative of safeguarding Indonesia's invaluable rainforests, as well as the welfare of its local populations and biodiversity.

Furthermore, traditional extraction methods are frequently labour-intensive and time-consuming, which can increase production expenses and restrict production scale (Paek et al., 2005). This can be an impediment to entrance for small-scale producers who lack the capital to invest in the apparatus and labour necessary for traditional extraction methods. In summary, the limitations and difficulties of traditional extraction methods emphasize the need for more sustainable and efficient extraction methods that can resolve these issues while still producing high-quality natural products.

3.3. Environmental impacts of traditional techniques

Traditional extraction methods in Indonesia can have negative environmental effects, especially in relation to the use of significant quantities of solvents and the depletion of natural resources (Yara-Varón et al., 2017). The solvents used in conventional extraction techniques can be toxic and detrimental to the environment, and their disposal can lead to soil and water contamination (Misra and Pandey, 2005). In addition, the use of significant quantities of solvents can contribute to greenhouse gas emissions and air pollution (Korre et al., 2010). Depletion of natural resources, particularly plant species used for extraction, is another environmental impact of traditional extraction techniques (Putra et al., 2023). This can have negative effects on local ecosystems and communities. In addition, the removal of particular plant species may contribute to deforestation and habitat devastation, thereby exacerbating the loss of biodiversity.

In addition, the use of conventional extraction methods may result in the production of wasted materials that require disposal (Sharma et al., 2016). For instance, the extraction of specific plant materials may result in the production of waste biomass that must be disposed of properly to prevent adverse environmental effects (Mohd Faizal et al., 2022). Thus, the environmental impacts of traditional extraction techniques demonstrate the need for the development and adoption of more sustainable and environmentally favourable extraction methods that can mitigate negative environmental impacts while still producing high-quality natural products.

Energy consumption is another environmental impact of traditional extraction methods including Soxhlet extraction (Ivanovs and Blumberga, 2017). Soxhlet extraction frequently involve high temperatures and lengthy extraction periods, which can necessitate substantial quantities of energy (Chemat et al., 2012). This can contribute to greenhouse gas emissions and other environmental impacts related to the production and consumption of energy. In addition to the direct environmental effects of conventional extraction methods, indirect effects related to land use and land management may also occur. In addition, the environmental impacts of conventional extraction methods can have an effect on the global market for natural products. As consumers become more aware of the environmental and social impacts of the products they purchase, the demand for sustainably sourced and manufactured natural products rises. This creates a market incentive for the development and adoption of more environmentally responsible and sustainable extraction methods.

As a result of these obstacles, there is a growing interest in the development of green extraction techniques that can mitigate negative environmental impacts and promote sustainability while still producing high-quality natural products. Green extraction techniques rely on the use of sustainable solvents, low-energy extraction methods, and other eco-friendly technologies to extract natural products with minimal environmental impact. By employing more sustainable and eco-friendly extraction methods, Indonesia can help satisfy the growing demand for natural products while minimizing negative environmental impacts and fostering social and economic sustainability. In addition to supporting the growth of Indonesia's natural products industry, the development and adoption of green extraction techniques can contribute to the country's economic development.

4. Green extraction techniques

Green extraction techniques are gaining popularity for the extraction of natural products. These techniques employ eco-friendly solvents and processes to mitigate adverse environmental effects, reduce energy consumption, and improve the quality of natural products (Golmakani et al., 2017; Sarah et al., 2023; Tambun et al., 2021; Variyana et al., 2019). Indonesian natural products have been extracted using supercritical fluid extraction (SFE), pressurized liquid extraction (PLE), and microwave-assisted extraction (MAE) (Dandekar and Gaikar, 2002; Hosseini et al., 2016; Kusuma et al., 2018; Ranitha et al., 2014).

Traditional extraction techniques in Indonesia have limitations and difficulties, such as the use of hazardous solvents, low selectivity, and inefficiency, which can lead to negative environmental impacts and diminished product quality (Guan et al., 2007). In contrast, green extraction techniques offer a number of benefits, including reduced environmental impact, increased efficiency and selectivity, decreased energy consumption, improved product quality, and increased market competitiveness (Clark, 1999; Picot-Allain et al., 2021; Romano et al., 2022).

The use of green extraction techniques can promote the sustainable growth of Indonesia's natural products industry, which is vital to the country's economy and millions of people's means of subsistence. In addition to contributing to the global market's growing demand for sustainable and eco-friendly products, green extraction techniques can also help meet this demand. Therefore, it is crucial to conduct additional research and develop environmentally friendly extraction techniques for Indonesian natural products in order to improve their quality, increase their value, and promote sustainable development. Several green extraction techniques have been developed and used for Indonesian natural products. These include:

4.1. Supercritical fluid extraction (SFE)

Supercritical fluid extraction (SFE) is an ecological extraction technique that has been used to extract natural products (Easmin et al., 2015). SFE utilizes fluids that are above their critical temperature and pressure, known as supercritical fluids, to extract the desired compounds from the starting material. The most commonly used supercritical fluid in SFE is carbon dioxide (CO_2) (Abdul Aziz et al., 2022). SFE has several advantages over conventional extraction methods, including the use of non-toxic and non-combustible solvents, high selectivity, and the capability to extract compounds at low temperatures, which can help preserve the purity of natural products (Argun et al., 2022). The scalability of SFE makes it appropriate for industrial applications (Carvalho et al., 2015). In addition, the use of SFE can reduce the quantity of residue produced during the extraction procedure. As supercritical fluids are readily recyclable, SFE produces less residue than conventional extraction methods. This can aid in reducing the environmental impact of Indonesia's natural products industry.

Several studies have examined the application of SFE to Indonesian natural products. SFE has been used, for instance, to extract essential compounds from Indonesian spices like nutmeg, cinnamon, and clove

(Machmudah et al., 2006). SFE also can be used to extract bioactive compounds from medicinal plants native to Indonesia, including ginger, turmeric, and soursop. In addition, it has been demonstrated that SFE is effective at extracting a variety of bioactive compounds from Indonesian natural products. Various Indonesian plant species, such as *Orthosiphon aristatus, Phyllanthus niruri*, roselle and *Zingiber officinale*, can be extracted using SFE to obtain flavonoids, alkaloids, terpenoids, and essential oils (Abdul Aziz et al., 2020a, 2020b; Redzuan et al., 2021). Additionally, SFE can be used to derive natural colors from Indonesian sources, such as the red pigment astaxanthin from *Haematococcus pluvialis* algae (Thana et al., 2008). The use of SFE for the extraction of natural hues can provide an alternative to the frequently used synthetic colors in the food and cosmetics industries (Rizkiyah et al., 2023; Rymbai et al., 2011; Vatai et al., 2008).

Nonetheless, SFE has limitations that must be considered. The costly equipment and operating expenditures are one of the main limitations (Cavalcanti et al., 2012, 2011). Equipment for supercritical fluid extraction can be quite expensive, and the procedure requires specialized knowledge. In addition, SFE may not be suitable for certain categories of natural products, as certain compounds may be difficult to extract using supercritical fluids especially for non-polar compounds (Arumugham et al., 2021). Overall, SFE is a promising environmentally friendly extraction method for the extraction of natural products in Indonesia. It provides several advantages over conventional extraction methods, including reduced environmental impact, high selectivity, and the capacity to extract compounds at low temperatures (Mohd-Nasir et al., 2021; Putra et al., 2020). To improve the efficiency and selectivity of SFE for Indonesian natural products, additional research is required to optimize the process parameters and examine the use of alternative supercritical fluids. Table 2 shows the parameters effect on supercritical fluid extraction on yield recovery for natural plants and herbs.

4.2. Pressurized liquid extraction (PLE)

Pressurized liquid extraction (PLE) is an environmentally friendly extraction method that employs a high-pressure solvent to extract desired compounds from unprocessed materials. PLE has been used to extract bioactive compounds from a variety of Indonesian natural products, including medicinal plants and fruits. A benefit of PLE is its high extraction efficacy, which is a result of the process's use of high pressure and temperature. Additionally, PLE can be conducted at comparatively low temperatures, which can aid in preserving the stability and bioactivity of the target compounds. In addition, PLE generates less waste than conventional extraction methods, making it an environmentally preferable alternative.

Table 2
Parameters effect on supercritical fluid extraction on yield recovery.

Extraction parameter	Effect of increasing	Effect of decreasing	Ref
Pressure	Increases solubility of compounds in the supercritical fluid, leading to higher yields and faster extraction rates.	Decreases solubility of compounds in the supercritical fluid, leading to lower yields and slower extraction rates.	(Arsad et al., 2023; Rizkiyah et al., 2023)
Temperature	Increases extraction rate and selectivity of certain compounds, but can also lead to thermal degradation of heat-sensitive compounds.	Decreases extraction rate, but may help to preserve heat-sensitive compounds.	(Abdul Aziz, Mohd Idrus, et al., 2022)
CO_2 Flow Rate	Increases extraction rate, but may also increase the amount of impurities extracted.	Decreases extraction rate and can lead to incomplete extraction.	(Idham et al., 2021)
Co-solvent Addition	Increases solubility of certain compounds, leading to higher yields and increased selectivity.	Can lead to increased solvent costs and potential environmental concerns.	(Idham et al., 2021; Putra et al., 2021)

From Indonesian natural products, such as flavonoids, alkaloids, and phenolic compounds, PLE has been used to extract a vast array of bioactive compounds, including flavonoids, alkaloids, and phenolic compounds. PLE has been used, for instance, to extract phenolic compounds from the leaves of soursop (*Annona muricata*), an Indonesian tropical fruit commonly used in traditional medicine (de Moraes et al., 2020). *Andrographis paniculata, Curcuma longa*, and *Orthosiphon stamineus* are examples of Indonesian medicinal plants from which bioactive compounds have been extracted using PLE (Abubakar, 2016; Osorio-Tobon et al., 2014; Pang et al., 2014).

However, similar to other traditional extraction methods, PLE has its limitations. Small-scale producers can be hindered by the high cost of apparatus, which is one of the main limitations (Picot-Allain et al., 2021). In addition, the high pressure and temperature employed in PLE can affect the stability and quality of certain compounds, resulting in their degradation and loss of bioactivity (Oliveira et al., 2022). An intriguing application of PLE in Indonesia is the extraction of bioactive compounds from the medicinal plant *Centella asiatica*, which is extensively used in traditional medicine for its neuroprotective and wound-healing properties (de Souza et al., 2019; Ruksiriwanich et al., 2020) . PLE has been demonstrated to be an effective extraction method for triterpenoids, the primary bioactive compounds in *Centella asiatica*. It has been demonstrated that the extracted triterpenoids possess neuroprotective and anti-inflammatory properties, making them viable candidates for the treatment of neurological and inflammatory diseases.

PLE has also been used to extract bioactive compounds from *Melastoma malabathricum*, a medicinal plant with anti-inflammatory and anti-diabetic properties used in traditional medicine (Khanum, 2021). The extracted phenolic compounds showed thepotent antioxidant and anti-diabetic properties, suggesting their potential application in the food and pharmaceutical industries. The extraction of essential oils from aromatic plants such as lemongrass, patchouli, and ginger can be applied for an additional intriguing application of PLE in Indonesia (Kamaruddin et al., 2022; Sarah et al., 2023; Soh et al., 2020). It has been demonstrated that PLE is an effective method for extracting essential oils, with high yields and brief extraction durations. The extracted essential oils contain an abundance of bioactive compounds, such as terpenes and phenolics, which possess antimicrobial, antioxidant, and anti-inflammatory properties. There are prospective applications for these essential oils in the food, cosmetic, and pharmaceutical industries.

In Indonesia, PLE has also can be used to extract bioactive compounds from marine sources such as seaweeds and sponges (Montero et al., 2023; Perez-Vazquez et al., 2023). It was discovered that PLE is an effective method for extracting sulfated polysaccharides from brown seaweeds, which exhibit a variety of biological activities, including anticoagulant and antitumor properties. PLE has also been used to extract bioactive compounds from sponges, such as alkaloids and terpenoids, which exhibit diverse pharmacological activities, including anticancer and antiviral activities. PLE is a prospective green extraction technique for the extraction of natural products in Indonesia, with applications in the food, cosmetic, and pharmaceutical industries. It is a viable option for the extraction of bioactive compounds from various natural sources due to its high extraction efficiency and reduced environmental impact. Optimizing the process parameters and investigating the potential of PLE for the extraction of other bioactive compounds from Indonesian natural products requires additional research. Table 3 shows the parameters effect on PLE on yield recovery for natural plants and herbs.

Table 3
Parameters effect on PLE on yield recovery for natural plants and herbs.

Parameter	Effect of increasing	Effect of decreasing	Ref
Temperature	Increasing the temperature increases the solubility of the target compound in the solvent, resulting in a higher yield.	Decreases selectivity: If the temperature is too high, it can cause thermal degradation of the target compound or co-extraction of unwanted compounds, reducing the selectivity of the extraction process.	(de Souza et al., 2019; Perez-Vazquez et al., 2023)
Pressure	Increasing the pressure increases the solubility of the target compound in the solvent, resulting in a higher yield.	Decreases selectivity: If the pressure is too high, it can cause structural changes in the plant material, resulting in the extraction of unwanted compounds or reducing the selectivity of the extraction process.	(Farías-Campomanes et al., 2014; Krstić et al., 2023; Osorio-Tobon et al., 2014; Osorio-Tobón et al., 2013)
Solvent flow rate	Increases yield: Increasing the solvent flow rate can help to increase the rate of extraction and improve the yield.	Decreases extraction efficiency: If the solvent flow rate is too high, it can result in incomplete extraction and a lower yield.	(Mustafa and Turner, 2011)
Extraction time	Increases yield: Increasing the extraction time allows for more complete extraction of the target compound, resulting in a higher yield.	Decreases selectivity: If the extraction time is too long, it can result in the extraction of unwanted compounds and reduce the selectivity of the extraction process.	(Abubakar, 2016)

4.3. Microwave-assisted extraction (MAE)

Microwave-assisted extraction (MAE) is a comparatively novel ecological extraction method that is gaining popularity in Indonesia for the extraction of natural products. MAE utilizes microwave radiation to heat the sample and extract the desired compounds, resulting in shortened extraction times, increased yields, and decreased solvent consumption. The extraction of bioactive compounds from traditional medicinal plants such as *Curcuma longa, Zingiber officinale*, and *Andrographis paniculata* (Abubakar, 2016) can be applied for MAE in Indonesia (Dandekar and Gaikar, 2002; Kamaruddin et al., 2022). MAE has been demonstrated to be an effective technique for the extraction of various bioactive compounds, including curcuminoids, gingerols, and andrographolides, which exhibit various pharmacological activities, including anti-inflammatory, antioxidant, and antiviral activities (Kyriakoudi et al., 2021).

MAE has the advantage of being readily scalable for industrial applications. MAE can be carried out in bulk or continuous mode, making it appropriate for large-scale extractions. In addition, MAE can be combined with other environmentally friendly extraction methods, such as SFE and PLE, to improve the extraction efficiency and yield of target compounds. MAE can be utilized to extract bioactive compounds from Indonesian fruits like mango and pineapple (del Pilar Sánchez-Camargo et al., 2021; Mala et al., 2021). MAE was discovered to be an effective method for the extraction of phenolic compounds from mango peels and pineapple crowns, which exhibit diverse biological activities, including antioxidant and antidiabetic activities. Food and pharmaceutical industries have prospective applications for the extracted phenolic compounds.

In addition, MAE has been used to extract essential oils from aromatic Indonesian plants, such as clove and cinnamon. It was discovered that MAE is a rapid and effective method for the extraction of essential oils, with high yields and brief extraction durations. The extracted essential oils contain numerous bioactive compounds with antimicrobial, antioxidant, and anti-inflammatory properties, such as eugenol and cinnamaldehyde. There are prospective applications for these essential oils in the food, cosmetic, and pharmaceutical industries.

Another difficulty associated with MAE is the possibility of non-uniform heating, which can result in varying extraction efficiencies and yields (Calinescu et al., 2017). This can be mitigated by utilizing the proper solvent mixtures and distributing the sample uniformly within the extraction vessel. In addition, the apparatus required for MAE can be relatively expensive in comparison to other environmentally friendly extraction methods, such as ultrasound-assisted extraction (UAE) and pressurized hot water extraction (PHWE). Therefore, the economic viability of MAE for large-scale natural resource exploitation in Indonesia must be thoroughly evaluated. Despite these obstacles, MAE has been used successfully to extract various natural products from Indonesian sources, such as ginger, turmeric, and nutmeg. In some instances, it has been demonstrated that MAE is more effective than conventional extraction methods, such as Soxhlet extraction and maceration. Overall, MAE is a prospective environmentally friendly extraction method for Indonesian natural products, with advantages such as high extraction efficacy, reduced solvent consumption, and industrial scalability potential. To optimize the process parameters and evaluate the economic viability of MAE for large-scale extraction of natural products in Indonesia, additional research is required. Table 4 shows the parameters effect on MAE on yield recovery for natural plants and herbs.

4.4. Comparison traditional and established green extraction techniques

In recent years, green extraction techniques have emerged as an alternative to traditional extraction methods due to their eco-friendliness and higher efficiency. This section will compare traditional and established green extraction techniques used for Indonesian natural products. One of the most widely used traditional extraction techniques in Indonesia is maceration. This technique involves immersing plant material in a solvent for an extended period to extract the desired compound. However, the process is time-consuming, and the resulting extract may be contaminated with impurities from the solvent, reducing its purity and efficacy (Zhang et al., 2018). Compared to maceration, established green extraction techniques such as SFE, PLE, and MAE offer several advantages, including faster extraction times, higher selectivity, and reduced solvent usage. For example, SFE is a non-toxic and environmentally friendly method that uses supercritical carbon dioxide (CO_2) as a solvent (Ha et al., 2008; Nasir et al., 2017). This technique has been successfully applied to extract essential oils from Indonesian medicinal plants, yielding high-quality extracts with minimal solvent residue and a high concentration of bioactive compounds.

Another established green extraction technique is PLE, which uses pressurized solvents at elevated temperatures to extract compounds

Table 4
Parameters effect on MAE on yield recovery for natural plants and herbs.

Parameter	Effect of increasing	Effect of decreasing	Ref.
Solvent-to-sample ratio	Increases extraction efficiency, but can also lead to increased solvent usage and environmental impact	Decreases extraction efficiency and may lead to incomplete extraction	(Alvi et al., 2022; Sarah et al., 2023; Zamanhuri et al., 2021)
Microwave power	Increases extraction efficiency and reduces extraction time	Decreases extraction efficiency and may result in incomplete extraction	(Fernández-Marín et al., 2021)
Extraction time	Increases extraction efficiency and yield up to a certain point, after which yield may plateau or decrease	Decreases extraction efficiency and yield: If the extraction time is too long, it can result in the extraction of unwanted compounds and reduce the selectivity of the extraction process.	(Zamanhuri et al., 2021)
Temperature	Increases extraction efficiency and yield up to a certain point, after which yield may plateau or decrease	Decreases selectivity: If the temperature is too high, it can cause thermal degradation of the target compound or co-extraction of unwanted compounds, reducing the selectivity of the extraction process.	(Li et al., 2010)
pH	Can affect the solubility and stability of target compounds, but may not significantly affect extraction efficiency in some cases	May affect extraction efficiency in some cases, but generally has a smaller impact than other parameters	(Oke et al., 2023)
Additives (e.g. salt, acid)	May increase extraction efficiency and yield by altering the solubility of target compounds or breaking down cell walls	May not have a significant effect on extraction efficiency in some cases, and may increase environmental impact if used excessively	(Chan et al., 2011)

from plant material. This method can extract a wide range of compounds, including polar and nonpolar compounds, making it suitable for various natural product extractions. PLE can be applied to extract bioactive compounds from Indonesian medicinal plants, including alkaloids, flavonoids, and terpenoids. MAE is another green extraction technique that uses microwave energy to extract bioactive compounds from plant material. This method has been shown to be more efficient than traditional extraction methods, with shorter extraction times and higher yields (Dandekar and Gaikar, 2002; Mandal et al., 2007). MAE can be utilized to extract flavonoids and alkaloids from Indonesian medicinal plants such as *Curcuma xanthorrhiza* and *Andrographis paniculata*.

Despite the benefits of established green extraction techniques, there are still some limitations that need to be addressed. One of the main challenges is the high cost of equipment required for these techniques, which can be a significant barrier to their widespread adoption. Additionally, the high pressures and temperatures used in these methods can affect the stability and activity of some compounds. In conclusion, green extraction techniques offer a promising alternative to traditional extraction methods for Indonesian natural products. Compared to traditional methods, established green extraction techniques such as SFE, PLE, and MAE offer several advantages, including faster extraction times, higher selectivity, and reduced solvent usage. While these techniques have some limitations, ongoing research aims to improve their efficiency and overcome their challenges.

Fig. 2 shows that MAE is the most popular method to extract the natural products instead of SFE and PLE. Microwave-assisted extraction (MAE) has gained significant popularity as a method for extracting natural products compared to supercritical fluid extraction (SFE) and pressurized liquid extraction (PLE). This widespread adoption can be attributed to several key factors. Firstly, MAE is renowned for its exceptional speed and efficiency, enabled by the use of microwave energy to rapidly heat the sample and solvent, resulting in reduced extraction times compared to SFE and PLE. Secondly, MAE offers a more cost-effective option, as the equipment is generally more affordable and accessible than the specialized systems required for SFE and PLE. Moreover, MAE's ease of use and automation capabilities contribute to its popularity, requiring less manual intervention during the extraction process compared to SFE and PLE, which involve more complex procedures. Additionally, MAE's versatility stands out, as it can be applied to a wide range of sample types, making it suitable for various natural product extraction scenarios. Furthermore, it has shown to deliver excellent yields of target compounds and allows for easy adjustments to achieve selective extractions, enhancing its applicability in different research areas. However, it is important to consider that the choice of extraction method may vary depending on specific compounds, sample matrices, available resources, and evolving research advancements in each technique.

5. Challenges and limitations of green extraction in Indonesia

Although green extraction techniques offer numerous advantages over conventional extraction methods, their widespread adoption and use in Indonesia still faces obstacles and restrictions. For the widespread adoption and use of green extraction techniques for Indonesian natural products, it will be essential to address these challenges and limitations. This will necessitate investments in research and development, the sharing of knowledge and expertise, and the creation of appropriate policies and regulations to facilitate the adoption of green extraction techniques. Among the most significant obstacles and limitations are:

- In Indonesia, the green extraction techniques used for natural products lack standardization. This makes it challenging to compare the results of various studies and can hinder the reproducibility of the extraction procedure.
- Some green extraction techniques, including SFE and MAE, require specialized apparatus that may not be broadly available in Indonesia. This can hinder the spread of these techniques, especially in rural areas.
- The high cost of apparatus for some green extraction techniques may prevent small and medium-sized enterprises (SMEs) in Indonesia from adopting them.
- Some ecological extraction methods, such as SFE and PLE, are more complicated than conventional extraction methods. This can make them more challenging to embrace and implement in particular contexts.

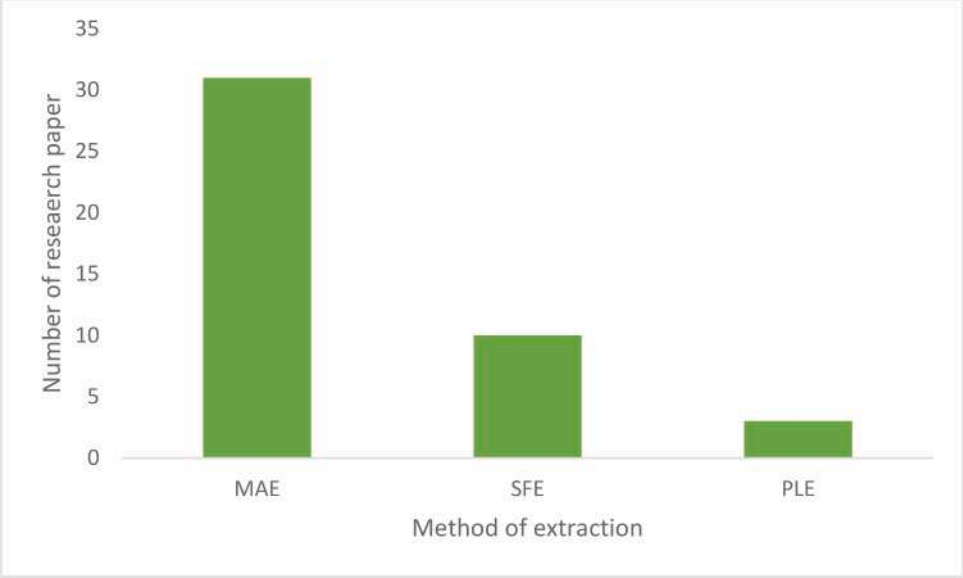

Fig. 2. Numbers of research papers published in SCOPUS related to green extraction for natural products (1st keyword: Microwave assited extraction in Indonesia; 2nd keyword: Supercritical fluid extraction in Indonesia; 3rd keyword: Pressurize liquid extraction in Indonesia time accessed: 25 July 2023).

- Limited knowledge and expertise: Researchers, scientists, and industry professionals in Indonesia lack knowledge and expertise in ecological extraction techniques. This may restrict their adoption and application in the extraction of natural products.
- Scale-up challenges: While green extraction techniques have been effectively scaled up in some industries, such as the agricultural and pharmaceutical industries, scaling up these techniques for the extraction of natural products in Indonesia still presents challenges.
- Green extraction techniques can have an effect on the quality of the extracted natural products, particularly in terms of their chemical composition and bioactivity. Depending on the extraction technique and natural product, this can be both advantageous and disadvantageous. For the commercialization and use of green extraction techniques, ensuring consistent product quality will be essential.
- Compatibility with traditional knowledge and practices pertaining to the extraction of natural products in Indonesia may not always be compatible with ecological extraction techniques. It will be necessary to consider how to effectively and respectfully integrate these traditional practices with new ecological techniques.
- The adoption of green extraction techniques in Indonesia may encounter regulatory challenges relating to safety, efficacy, and quality control. To ensure the safety and efficacy of extracted natural products, it will be necessary to develop appropriate regulations and guidelines.
- The adoption of green extraction techniques will ultimately depend on the market's demand for sustainably sourced and environmentally favourable natural products. In order to promote the adoption of green extraction techniques in Indonesia, it will be necessary to increase consumer awareness and demand for green products.

6. Advancements in green extraction techniques for Indonesian natural products

To completely actualize the potential of these ecological extraction techniques, it is necessary to address a number of obstacles and limitations. The lack of standardized protocols for these techniques is a significant obstacle, as it can result in variations in extraction efficiency and product quality. The high cost of apparatus and reagents associated with some of these techniques, such as SFE and PLE, is another obstacle. This can make them less accessible to small-scale producers, who may continue to utilize conventional extraction methods.

In addition, there is a need for additional research on the environmental impacts and long-term viability of these green extraction techniques. It is essential that these techniques do not merely transfer environmental burdens to other areas or exacerbate other sustainability issues. In addition, there has been an emphasis on the development of more affordable and accessible apparatus for these techniques, such as the use of recycled materials and the creation of low-cost, portable extraction systems. Furthermore, the significance of community participation and empowerment in the development and adoption of green extraction techniques has been increasingly acknowledged. This includes the participation of local communities in the research and development process, as well as the propagation of local knowledge and traditional extraction techniques alongside the use of more modern, environmentally friendly extraction techniques.

Lastly, there is a need for increased collaboration between researchers, industry, and local communities in order to fully comprehend the potential of these green extraction techniques and develop solutions tailored to the specific needs and circumstances of Indonesian natural product producers. Despite these obstacles, the advances in green extraction techniques for Indonesian natural products represent a significant step toward more sustainable and effective natural product extraction. These techniques have the potential to benefit both the environment and the livelihoods of Indonesian communities if further research and development are conducted.

7. Summary

On the basis of the review of ecological extraction techniques for Indonesian natural products, it is possible to recapitulate several main findings. Traditional extraction techniques in Indonesia have a number of drawbacks and obstacles, including low extraction efficacy, lengthy extraction times, and negative environmental impacts. As alternatives to conventional extraction methods, green extraction techniques such as SFE, PLE, and MAE have been developed and have shown promising results in terms of higher extraction efficiency, shortened extraction time, and lower environmental impacts.

However, there are still obstacles and constraints in the application of green extraction techniques in Indonesia, including high equipment and operational costs, limited availability of trained personnel, and a lack of standardization in extraction procedures. To surmount these obstacles and promote sustainable extraction practices in Indonesia, it is

necessary to cultivate local expertise in the field of green extraction, enhance equipment accessibility and affordability, and establish green extraction standard operating procedures. This review has significant implications for sustainable extraction practices in Indonesia. Indonesia can mitigate the environmental impact of natural product extraction, reduce operational costs, and increase the value and competitiveness of Indonesian natural products on the global market by implementing green extraction techniques. Moreover, sustainable extraction practices can contribute to the conservation of biodiversity and the preservation of Indonesia's natural resources.

Future research and development in the field of green extraction for Indonesian natural products is recommended to include the exploration of new and innovative green extraction techniques, the optimization of existing techniques for specific natural products, the establishment of a database of green extraction protocols and parameters, and the development of partnerships between academia, industry, and government agencies to promote sustainable extraction practices in Indonesia. By addressing these research priorities, Indonesia can maintain its commitment to sustainability and environmental stewardship while maintaining its position as the world's foremost exporter of natural products.

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Data availability

The data that support the findings of this study are available from the corresponding author, upon reasonable request.

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CRediT authorship contribution statement

Nicky Rahmana Putra: Conceptualization. **Yustisia Yustisia:** Visualization, Investigation, Writing – review & editing. **R. Bambang Heryanto:** Visualization, Investigation, Writing – review & editing. **Asmaliyah Asmaliyah:** Visualization, Investigation, Writing – review & editing. **Miswarti Miswarti:** Visualization, Investigation, Writing – review & editing. **Dwila Nur Rizkiyah: . Mohd Azizi Che Yunus:** Supervision. **Irianto Irianto:** Writing – review & editing. **Lailatul Qomariyah:** Writing – review & editing. **Gus Ali Nur Rohman:** Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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