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Oilseed Crops

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Edited by Mirza Hasanuzzaman
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Meet the editors

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Contents

Preface

Oilseeds are one of the most dynamic components of global agriculture, their annual growth rate of 4.1% having exceeded agricultural and livestock output growth over the last three decades. Oilseed crops belong to a variety of plant groups, and oil is their most valuable by-product, both as a food source and feedstock. Different oilseed crops have varying oil contents, ranging from 20% for soybean to 40% for sunflowers. Oilseed is also a raw material for a variety of oleochemical enterprises. The manufacture of soaps, detergents, greases, lubricants, and candles has traditionally been the primary non-food use for the by-products of oilseed crops. Soybean, sunflower, *Brassica*, canola, coconut, oil palm, rapeseed, peanuts, rice, olive and cotton are some of the most common and important oilseed crops in the world. While soybean and sunflower require high temperatures, cool climatic conditions are suitable for the cultivation of major oilseed crops like *Brassica* spp., with their considerable economic and nutritional value. The genus *Brassica* belongs to the Brassicaceae family, which has nearly 435 genera and 3675 species. Plants of the *Brassica* genus are well-known as edible oil, vegetables, and silage, and are the most important oil crops in some Asian countries. Cultivation of these crops has increased dramatically over the past few decades, reaching more than 300 million hectares in 2014. Due mainly to their use in industries and potential as biofuels, oilseed crops are playing an important role in the reduction of demand for fossil fuels. The growing global population is increasing the demand for edible oils, although only about 7.5 million tons are produced annually. In order to increase oilseed crop production and global competitiveness, researchers must seek out the best conventional and molecular approaches.

The six chapters in this book deal with the physiological and molecular mechanisms of oilseed crops and discuss various aspects of oilseed production and use. We believe that this book is will be useful for undergraduate and graduate students, teachers, and researchers, particularly from in the fields of Agronomy and Crop Science.

We would like to thank all the authors for their outstanding and timely contributions. We are very grateful to Lucija Tomicic-Dromgool, Commissioning Editor, and to Jasna Bozic and Marina Dusevic, Author Service Managers, at IntechOpen for their prompt responses during the production of this book. We also thank Farzana Nowroz, Ayesha Siddika and Md. Rakib Hossain Raihan for reviews and formatting.

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Chapter 1

Oilseed Rape: Biology, Use, Current Cultivation Issues and Agronomic Management

Elžbieta Jankovska-Bortkevič, Sigita Jurkonienė,
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Abstract

Oilseed rape is an economically crucial agricultural crop widely grown in many countries. It is an herbaceous plant which belongs to the *Brassicaceae* family and, according to the nature of vegetation, is present in spring and winter subspecies. Over the years, the area of oilseed rape increased due to its widespread use for producing technical and food oil, fuel and other market needs. Oilseed rape oil is one of the most widely used food oils on the globe. It is valued for its high content of unsaturated fatty acids and odorlessness. The yield of oilseed rape mainly depends on its genetic potential, agronomic management, and environmental conditions. Thus, oilseed rape growers worldwide meet not only common, but also climate zone-specific agronomic issues, e.g., various unfavourable abiotic and biotic factors characteristic to a particular climate zone. Thanks to the efforts of breeders, scientists, and chemical companies, the solutions to the big problems such as disease resistance, lodging, delayed harvest, weed, pest and pod shatter control, are already available and still under search aiming to reveal the full potential of the cultivars.

Keywords: abiotic stress, *Brassica napus*, canola, environmental factors, oil, pests, seeds, weeds

1. Introduction

Oilseed rape (*Brassica napus* L.) is among the oldest crops grown in the world. It belongs to the flowering plant family *Brassicaceae*. This family is also called *Cruciferae* or the mustard family. It includes around 3 thousand plant species. The characteristic attribute of plants from this family is the arrangement of four flower petals in the shape of a cross. Historically, many species from the *Brassicaceae* family, e.g., brown and oriental mustard, Brussels sprouts, broccoli, cabbage, cauliflower, kale, kohlrabi, napa, oilseed rape, rutabaga, turnip, etc. have been cultivated for their edible parts: buds, flowers, leaves, roots, stems, and seeds. Oilseed rape is currently one of this family's most widely cultivated members [1–3].

Due to the absence of populations of its wild form, the origin of oilseed rape is not fully elucidated. However, the available knowledge suggests that this herbaceous plant originated from the eastern Mediterranean and west Asian region. It is supposed to be derived about seven and a half years ago from spontaneous hybridisation between turnip rape (*Brassica rapa* L.) and cabbage (*Brassica oleracea* L.). The studies suggest that currently, several B. napus subgenomes are present: the subgenome evolved from the ancestor of European turnip, and the subgenome evolved from the common ancestor of broccoli, cauliflower, Chinese kale and kohlrabi [1, 2, 4].

Historical records indicate that the cultivation of *Brassica* genus by humanity started many years ago. Plants from this genus are known to be widely cultivated by humans more than 10 thousand years ago. Oilseed rape was cultivated in India for more than 6 thousand years and spread to China and Japan 2 thousand years ago. Later, starting from the 13th century, due to the ability to grow in relatively low temperatures and successfully reproduce with little heat, oilseed rape was cultivated in Europe. The seeds of early oilseed rape varieties were avoided to use as a food oil source, as they contained high levels of erucic acid, which has a bitter taste and can cause heart diseases. However, these negative aspects were ignored by the poor during times of poverty and crisis [1, 3, 5].

In the following centuries, oilseed rape had a limited industrial use. Apart from being used for edible purposes, due to its oil property of emitting white smokeless flame when burning, since the 16th century, it was also widely used for lighting. The list of oilseed rape application possibilities expanded with the development of steam power. During this period, the unique property of oilseed rape oil to stick to water and steam-washed metal surfaces better than other lubricants was discovered. The great need for oilseed rape oil as a lubricant for rapidly increasing forces during World War II also affected the expansion of global B. napus seeded areas. For example, before World War II, oilseed rape was grown only in small trials for research purposes in Canada. The results of these trials revealed the ability of oilseed rape to grow both in eastern and western parts of this country and stimulated the expansion of this plant [1, 3].

Another surge in the worldwide interest in oilseed rape in the 20th century appeared when in the 1970s, the 0 and 00 type varieties with low erucic acid and glucosinolates were developed. Varieties grown until then did not meet the ever-increasing needs of edible oil and protein feed, as their seeds had up to 52% erucic acid and 8% glucosinolates. The first 00-type varieties were registered in Western Europe in 1986. Their seeds contained no more than 2% of erucic acid, no more than 20 μmol/g of glucosinolates of air-dried seeds, and no more than 40% of crude fat [2, 3].

Later, especially in the last decades, the cultivated areas expanded even more with the development of breeding, which resulted in the improvement of desirable traits (greater seed yield, earlier maturity, disease, and pod shatter tolerance). The new agronomical advantages allowed oilseed rape to be increasingly grown in new countries and under different conditions [2, 5].

2. Biology

The stem of oilseed rape is 100–180 cm in height. It is branched and covered with a waxy coating. The number of branches depends on the crop density. In the dense crops, 6–7 lateral branches are formed, and in the rarer ones, there are up to 20 branches. Oilseed rape leaves are green with a bluish tint, and covered with a waxy layer. The lower leaves, with stalks, lobed and curly, and the upper ones are lanceolate, without petioles. The rosette leaves turn yellow and fall before the formation of inflorescences [1, 6–8].

The colour of the oilseed rape flower is light yellow. It blooms for an average of 3 days. Flowers are arranged on racemes. Lateral racemes are located next to the apical raceme. Oilseed rape is a self-pollinating plant, so bees are not necessary for pollination. However, it has been found that oilseed rape that is visited by bees produces a higher seed yield, sets seeds faster, and matures them more consistently. The fruit is a 4–6 mm wide and 3–10 cm long self-opening pod with round seeds of various colour: brownish, brown, black, grey-black and yellowish. The type of oilseed rape root system is a taproot. Its main root penetrates the soil up to three meters deep. Lateral roots branch off in the upper part of the main root [3, 6, 9].

Several types of this plant were developed after its introduction to Europe. According to the nature of vegetation, oilseed rape includes spring (annual) and winter (biennial) subspecies. The botanical characteristics of spring and winter oilseed rape are similar. However, both forms have some distinctive features. The growth stages of spring and winter oilseed rape correspond, but they differ in duration [1, 3, 10].

The overall life cycle of oilseed rape includes a list of different growth stages: seed germination, seedling formation, leaf formation, stem growth, budding, flowering, pod development, seed maturation and stem drying (**Figure 1**) [8, 11].

Spring oilseed rape is sown in the spring, and stem development begins immediately after germination. The rosette is formed at higher temperatures under long day conditions. This stage of oilseed rape development lasts 30–40 days. The stem growth takes 8–10 days. The mass of roots of the spring-type oilseed rape is lower than that of the winter type. Larger lateral root branches of spring oilseed rape are found at 25–45 cm depth. Spring-type plants form 20–50 flowers in the apical raceme. Blossom spreads gradually from top to bottom in the inflorescence [12–14].

Winter oilseed rape is the original form of Brassica napus. It requires vernalisation which promotes flowering. One of the distinctive features of winter oilseed rape is the cessation of vegetation in winter and the renewal of vegetation in spring. The vegetation period of winter rape is 130–180 days. The total duration of oilseed rape growth is 270–320 days. It is sown in autumn and forms a rosette of 5–10 leaves on a short stem that remains in the soil surface during winter. The terminal bud of the rosette is raised above the soil surface by 2–3 cm [7, 11].

The intensive plant vegetation renews in the following spring. The growth of the long vertical stem and formation of 2–8 new leaves of the rosette begins when the average temperature reaches 2–9°C heat. In the stage of stem extension, the height of the plant increases rapidly, and the branching of the plant begins. Inflorescences

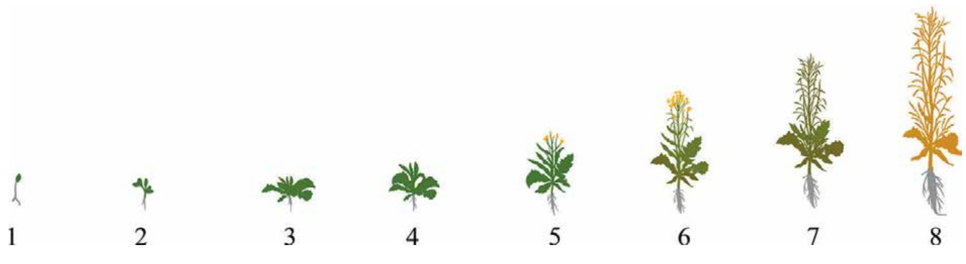

Figure 1.
Growth stages of oilseed rape life cycle: 1 - germination and emergence; 2 - leaf development; 3 - side-shoot formation; 4 - stem elongation/extension; 5 - inflorescence/flower-bud emergence; 6 – Flowering; 7 - pod/seed development and ripening; 8 – Senescence [8].

begin to form 15 days after the beginning of vegetation. The top of the stem is covered with leaves, and green inflorescences of tightly packed buds are situated between them. Winter-type plants form from 20 to 90 flowers in the apical raceme. The flowers of winter oilseed rape begin to blossom in the raceme from the bottom towards the top in the late spring. This period lasts 25–30 days. It is followed by the development of lateral branches. The total number of pods formed in winter and spring oilseed rape differs. It is higher in winter-type oilseed rape than in the spring type. The quantity of pods per plant in winter oilseed rape is from 200 to 500; in spring oilseed rape, it is from 80 to 200 pods. The average number of seeds per pod is 18-35. The average weight of 1000 seeds of winter rape is about 4–6 g [3, 6, 8, 14].

3. Prevalence

Different parts of our planet have different types of climates. Climate conditions in a particular area can determine the productivity of crops or even the ability to survive. Similarly to other crops, the prevalence of oilseed rape mainly depends on climatic conditions. It is widely cultivated in many places in the world. However, the length of the growing season is slightly variable in different climate zones. It is one of the few suitable oilseeds in the temperate zone. It grows well in relatively low temperatures, with less heat required for successful reproduction than other oilseed crops.

Moreover, the global geographical distribution of both winter and spring oilseed rape botanical forms also depends on the climatic conditions (**Figure 2**). Due to the fact that winter oilseed rape form requires the vernalisation to start the flowering process, its cultivation mostly dominates in Europe (EU countries, UK and Ukraine) and Asia. Spring oilseed rape varieties do not require vernalisation and are widely cultivated in the northern part of America, Europe, and Australia [3, 10, 15].

The global oilseed rape market consists of separate geographical segments: North America (United States, Canada, Mexico), Europe (Germany, France, Italy, Russia, United Kingdom, Spain), Asia-Pacific (China, India, Japan, Australia), Middle-East and Africa (United Arab Emirates, South Africa). Many of the world's oilseed rape market belongs to North America, the EU, and China. The major oilseed rape producers in North America are Canada, the USA, and Mexico. Oilseed rape grown in France, Germany and the United Kingdom comprises a more significant part (more than 80%) of European oilseed rape production [10, 16].

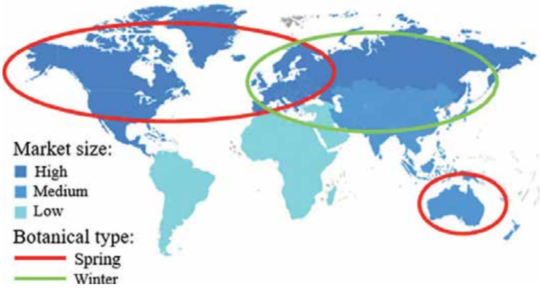

Figure 2.
Global oilseed rape market and prevalence of its spring and winter forms [10].

The studies show that oilseed rape production areas have been steadily growing with the increasing global demand for food, feed, fuel, and industrial applications. The need for oilseed rape production encourages farmers to expand their planted areas of oilseed rape. The global production of vegetable oils is expected to increase by 79–100% by 2050 [16–18].

4. The use of oilseed rape

Oilseed rape is an economically significant agricultural plant species. It is widely cultivated in many countries and is the world's second most crucial oilseed plant, which contains more than 40% of oil in its seeds. Thus, it is considered a very abundant source of oil. Oilseed rape seeds are the most widely used part of this plant. However, other parts of the oilseed rape plant are also useful [5, 15].

Oilseed rape seed oil and protein contents vary in different cultivars. The content of oilseed rape oil depends not only on the plant's genetic characteristics, but also on oil extraction conditions, e.g., solvent type, temperature, pressure, and time of processing. Many extraction methods have been tested, e.g., solvents, enzymes, gas, heat, or ultrasound. Some of these methods offer more advantages. These are safety for human consumption, less time-consuming, better oxidative stability and shelf-life, preservation or improvement of beneficial oil compounds. However, at the industrial level, the most commonly used type of extraction is the extraction by using hexane as a solvent. At the beginning of the process, seeds are heated for softening. Then they are flaked to break cell walls and cooked to promote cell disruption to release the oil. Later, residual oil is extracted using the solvent, and afterwards, the solvent is removed, and the oil is refined and processed. The negative feature of the extraction with hexane is a partial loss of beneficial antioxidants, phytosterols, and phenolic compounds [5, 19].

The types of fatty acids in the oil determine whether oil is used for edible or industrial purposes. Certain fatty acids, such as linoleic acid, are helpful for human health. They cannot be synthesised by the human body, thus must be obtained from the diet. And on the other hand, large concentrations of eicosenoic and erucic acids are harmful to human health [3, 7].

The oil obtained from the 00 cultivars is claimed to be safe both for infants and adults and is currently one of the most widely used vegetable food oils. It is valued for high nutritional value: high content of unsaturated fatty acids (which makes it more biologically valuable than animal fats), high oleic acid content, a favourable ratio of linoleic and linolenic acids, and abundance in vitamin E. It is also famous for its affordability, high cooking temperature, mild flavour and versatility as a cooking oil. It can be used at room temperature, e.g., as a salad dressing or for baking. In addition, it has been established that glucosinolate hydrolysis products can activate the human body 's protective mechanism. Glucosinolates are responsible for the pungent odour and taste, which ranges from the hot flavour in mustard seed and horseradish to the more subtle flavours of rutabaga and cauliflower. Therefore, the consumption of plants of the *Brassicaceae* family in the human diet may be associated with a lower risk of cancer [1, 3, 7, 20].

The high demand for oilseed rape oil is also related to the use of this oil for the production of biofuels. European Parliament promoted the use of biofuels by issuing Transport Biofuels Directive in 2003. It induced a dramatical increase in oilseed rape cultivation in Europe. The biodiesel produced from this renewable energy source is about 40% less polluting than diesel [1, 10, 15, 21].

Another valuable property of oilseed rape biodiesel is maintaining a fluid state even at low temperatures, and overdue of crystal formation, which makes it suitable for cold climates. Also, oilseed rape oil emits up to 90% less greenhouse gas (GHG) than fossil diesel. Thus, its use can reduce the emission of GHG from the transport sector and diminish the degradation of environmental wellness. What is more, oilseed rape biodiesel is biodegradable. It decomposes for about 30 days and accelerates the decomposition of diesel fuel when mixed. It is less toxic in water, thus reducing the impact of spills in sensitive areas. Biodiesel is often blended with fossil-fuel diesel in ratios of up to 20 per cent of biodiesel. Despite the numerous benefits, this biofuel also has disadvantages. It is vulnerable to oxidation during storage, and it can degrade some materials made of elastomer and rubber in fuel distributions. Also, due to the costs of growing, crushing, and refining oilseed rape oil, its price is higher than standard diesel fuel. Thus, biodiesel fuels are commonly made from used oil. Oilseed rape is used not only for producing edible oil, technical oil and biofuel, but also for other market needs [1, 3, 22].

A high erucic acid oilseed rape (HEAR) cultivar with erucic acid contents up to 66%, increased oil yield and increased tolerance to diseases and stress were used to make useful products, e.g. slip agent for the plastic film, emollient, food emulsifier, photographic material, ink, paper, textile, foam, plastics, etc. Moreover, oilseed rape can also be used in cosmetics and soap production. The soap is made in a cold process to save the beneficial compounds, light colour and dense. Coconut or other oils can be added to add to the aroma. Oilseed rape oil is also used as a biolubricant for biomedical applications (e.g., as a lubricant for artificial joints), as a personal lubricant or to replace 70% or more petroleum in chain saw oil. Besides, erucic, oleic and linoleic acids are helpful for maintenance of healthy hair and scalp conditions. Furthermore, a low-toxic and rapidly decomposing human and environment-safe pesticide was developed from oilseed rape oil. This insecticide is irritating and is used to fight aphids, loopers, worms, caterpillars, and mites [3, 5].

Oilseed rape meal, the residue after extraction, is widely used as a soil fertiliser, protein-rich and a functional additive for animals (cattle, pigs and birds) and human feed, as a substrate for fungi to produce enzymes (e.g., xylanase, xylosidase, cellulase, and acetyl–xylan esterase). Its incorporation in wheat, soybean, or corn-based diets affected feed efficiency, protein digestibility, energy value, and microbial community. It is also used in manufacturing capsules for bioactive drug delivery, cosmetics, and bioplastic packaging [5, 23].

Oilseed rape leaves, stems, roots, flowers, and seeds can be used for human food. Leaves and stems are a rich source of minerals, proteins, vitamins, and phenolic compounds. Their regular consumption is beneficial for human health by preventing chronic diseases. They can be used as edible vegetables or as a pot herb for seasoning. Oilseed rape flowers can be used as tea. Pollens can be consumed to strengthen the immune system and fight cancer. Seeds can be used as spices. Oilseed rape roots are also helpful due to their various diuretic, antigout, antiinflammatory, and antiscurvy characteristics [5, 9].

In animal husbandry, oilseed rape is used for green fodder and silage. Also, it is valued by beekeepers as a rich source of nectar and pollen for honeybees. It has been considered the main plant from which bees collect nectar. It has been shown that 1 hectare of oilseed rape yields 60–90 kg of honey. The period of oilseed rape flowering is about 1 month. Thus, oilseed rape provides good shelter and supplies nutrition for a long time. Oilseed rape honey has a mild medicinal, taste and aromatic properties. Its flavour is peppery, and the texture is soft-solid. It is whitish or milky yellow. It is often used as a sweetener, in confectionery and for processing [5, 24].

Oilseed rape is a deep-rooted plant that can absorb useful substances from deeper soil layers with its long taproot. Glucosinolates, formed from glucose and amino acid and containing sulphur, perform an essential defensive function in plants of the *Brassicaceae* family, protecting crops from pests and diseases. It releases volatile mustard oils and dissolves and assimilates nutrients that are difficult for other plants to obtain. After oilseed rape harvesting, many organic residues remain in the soil. It increases the amount of humus, improves the soil fertility, structure, and porosity, improves beneficial soil bacteria and alleviates or suppresses infections, nematodes and the growth of some weeds. Additionally, crop growth and development may be enhanced with the oilseed rape hormone brassinolide [3, 11, 12].

Due to these properties, oilseed rape is also grown as a green fertiliser and is an essential crop in many arable rotations. Often, it is grown as a break crop in three to four-year rotations with cereals (e.g., wheat and barley) and break crops (e.g., peas and beans). This provides many benefits for pest and disease control by reducing the possibility of pests and diseases being carried over from one crop to another. For example, it is helpful for wheat yield due to fungus-removing properties, when wheat is sown after sowing oilseed rape. Some cultivars of oilseed rape are also used as an annual forage [11].

Oilseed rape has a long flowering period. Its flowers are widely used for ornamental purposes, e.g., to decorate indoors and outdoors and as a field to visit for leisure. Hybridisation techniques enabled colourful (white, milky white, golden yellow, orange, purple, pink, and red) flowers [5, 9].

Oilseed rape plants can also be used for phytoremediation. Their roots can absorb and accumulate heavy metals from the soil rich in heavy metal contamination, e.g., cadmium (Cd). The absorbed heavy metal stems above and is removed when the plant is fully grown. Also, it has up to a three times higher rate of radionuclides uptake compared to other grains. Thus, it was researched as a tool to decontaminate the soil after the Chernobyl catastrophe [3, 5].

Finally, agricultural waste of oilseed rape is also useful. After its seeds are harvested, straws still contain a sufficient content of proteins, which is higher than wheat and legume. Thus, oilseed rape straw is used for animal feed. The only disadvantage of using straw as animal feed is a large amount of fibre, which lowers digestibility. However, it can be removed using ammonia treatments. Moreover, pods, stalks and cake are pressed and used for biofuel, as a substrate in vermicomposting and for the production of biochars [3, 5, 11].

5. Growth conditions and agronomic management

Oilseed rape seeds start to germinate at 2–3°C. However, the most favourable germination temperature is 12–16°C. Their seeds germinate at this temperature and normal soil moisture in 5–7 days. However, their germination may take up to 20–30 days in a dry period. The temperature over the growing season has a significant relationship with yield. The optimum temperature for oilseed rape growth is 20–21°C. Temperature higher than 30°C is harmful for pollination and shortens the pod and seed development phase, thus reducing yield and quality. Moreover, high temperature during winter hastens plant growth, shortens the growing season, and reduces yield potential [18, 25].

Winter oilseed rape withstands up to −3°C cold in autumn. And with a rosette containing 5–7 leaves, and a snow cover thicker than 6 cm, it withstands up to

−25°C frosts in winter. However, under snowless and frost conditions, or when the seedlings overwinter with only 3–4 leaves, the plants die at −12°C cold. Low temperatures mainly damage the root collars and terminal buds of winter oilseed rape. Also, winter oilseed rape is sensitive to spring temperature fluctuations, as the plant consumes many nutrients during the winter and is, therefore, most vulnerable at that time [25–27].

High yields of oilseed rape are obtained when the plants are optimally developed before flowering. For optimal growth, oilseed rape should be planted in a well-drained and finely tilted area with a pH ranging from 5.5 to 8.5 and with moderate soil salinity for optimal growth where *Brassica* crops have not been planted for at least 3 years. What is more, the level of the primary nutrients (nitrogen, phosphorus, potassium, and sulphur) should also be maintained. The requirement of nitrogen ranges from 45 to 70 kg per acre. The recommended rates of phosphorus range from 0 to 30 kg per acre, depending on the current levels in the soil. And the recommended rates of potassium range from 0 to 65 kg per acre according to present soil fertility levels.

Several types of tillage systems are currently used in oilseed rape cultivation. The conventional tillage system is the most commonly used type of tillage system. Parallelly, few alternative tillage systems are used, e.g., the reduced tillage. Nevertheless, it has no significant effect on the oilseed rape yield it is confirmed as the valuable alternative to conventional tillage due to lower fuel and labour consumption and sustainability. To ensure successful reduced tillage practice special conditions must be met. These are the diverse crop rotation, the use of combine with straw chopper and chaff spreader qualities [28–30].

Weed control is the other challenging task for oilseed rape growers. One of the important parts of weed control is the establishment of weed-free fields. Thus, grass and broad-leaved weeds should be targeted, and the oilseed rape seeds should be sown as soon as possible: for winter type – immediately after the harvest and for the spring type – as soon as soil moisture is sufficient for entry of machinery. Nevertheless, the use of herbicides is very effective weed control method, due to their presence in drinking water, health damaging properties and increasing herbicide resistance in certain weed species, the restrictions on herbicide use are getting tougher.

The type of tillage method also has an impact on weed potential. A higher risk of grass weeds and germination of cereal crop grain shed from previous harvest may be present when the soil is prepared by reduced tillage method, because seeds of some weed species after ploughed down in previous rotation may be ploughed back up to the soil surface. Thus, bearing in mind that some weed species have a durable seed-bank, and can reappear in ploughed soil, then 1 year at depth ploughing may be a good strategy for their control. The other tool for oilseed rape weed control is the use of various types of herbicides. E.g., non-selective herbicides are often used for weeding control in inter-row gaps, and the application of the residual herbicides is beneficial due to the season-long weed control. However, despite the success of herbicide applications there are few disadvantages of their use: herbicides are harmful for health and are being found in drinking water, herbicide effectiveness of certain herbicides has declined due to the increasing herbicide resistance in some weeds. The occurrence of these shortcomings resulted in introduction of legislation changes [31–33].

The maintenance of the optimal density of the crop is also essential. For oil production, oilseed rape is seeded directly into soil, aiming to achieve a density of 25–40 plants/m^2. Too dense crop leads to the formation of weak plants. Biometric analysis of the crops showed that weaker oilseed rape plants remain in the shooting stage. Thus, most of these plants are overshadowed by stronger and faster-growing oilseed rape plants and eventually die [3, 34].

The other mean factor for oilseed rape yield is the distribution of rainfall. The rainfall is undesirable after maturity. However, a long rainy season with sufficient rain and lower temperature during earlier developmental stages is very favourable [3, 10]. The sufficient humidity level in the soil is dramatically important for high oilseed rape yielding, especially during the stages of flowering, yield formation and ripening. Therefore, under conditions of water scarcity, irrigation needs to be applied to avoid the loss of yield. Studies have also showed that irrigation at the beginning of flowering improves nitrogen assimilation and oil content [35, 36].

A complex of actions and measures is taken to increase the yield of plants. One such action is the use of growth regulators. Aiming to improve oilseed rape yield (to stimulate growth and flowering, inhibit plant elongation and the opening of productive elements, protect against diseases and pests, enhance the quality of harvest and quantitative indicators, product nutrition, restore damaged plants and increase resistance to adverse environmental conditions, such as drought, flooding, cold etc.) a list of growth regulators (growth hormones, osmoregulators, retardants, fungicides, etc.) has been tested and used till now. Scientific studies show that the effect of exogenous compounds can cause physiological changes in the plant cell and change the defence response to biotic and abiotic environmental factors [3, 25, 37, 38].

6. Diseases and pest management

Oilseed rape plants can suffer from a comprehensive list of enemies, starting with the viruses and finishing with mammalians. Their main fungal diseases are canker, light leaf spot, *alternaria*, and *sclerotinia* stem rot. The canker symptoms are leaf spotting, premature ripening and stem weakening in the autumn-winter period. The treatment of fungicides conazole or triazole is applied in late autumn and spring to fight this disease. The light leaf spot disease is caused by the fungus *Pyrenopeziza brassicae*. This disease can be recognised by speckles of white spore pustules on leaves, stems and pods, which become visible only after a period of dry weather. *Alternaria* fungi species causes leaf spots. It can penetrate the pods and infect the seed. *Sclerotinia* is dangerous when lower main stems are infected. Infection can stop the food and water supply to the canopy and cause the death of the plant. Broad-spectrum fungicides are used to control *alternaria* and *sclerotinia* development [1, 39, 40].

Also, oilseed rape can be attacked by a wide variety of insects. The most common insect pests that attack oilseed rape are the cabbage stem flea beetle (CSFB), *brassica* pod midge, rape stem weevil, cabbage seed weevil, cabbage stem weevil, and pollen beetle. CSFB is currently the main oilseed rape pest enemy. Adults of CSFB graze on young oilseed rape plants and can cause plant death. CSFB larvae also mine within the petioles and stems of plants. Lower chances of CSFB spread are considered in areas where oilseed rape has not been grown recently or nearby [3, 40].

Despite continuously developing CSFB management relying on a variable and complex set of alternative solutions, it has recently become more challenging to control. First, due to a reduction in effective chemical control options: resistance to pyrethroid sprays and the withdrawal of neonicotinoid seed treatments. Foliar application of pyrethroid insecticides was the most approachable chemical control of CSFB in oilseed rape. However, the resistance to pyrethroid insecticides is now widespread, and lessens the control's potential. Thus, when CSFB resistance to pyrethroid insecticides has developed, measures must be taken. Subsequent pyrethroid applications are recommended to avoid. This is to stop the selection for resistance and harming natural enemies [3, 41].

Otherwise, it is essential to follow the spray thresholds and cure a full field. The decrease in effective chemical options in oilseed rape has spurred the rise of CSFB. Reducing oilseed rape areas in certain regions is often associated with a higher prevalence of CSFB. Thus, crop protection requires innovation in this pest management. There is a need to find novel approaches to control CSFB, e.g., breeding varieties with greater resilience to CSFB, using biopesticides or others. Presently there are no varieties available to control any pest of oilseed rape. Little attention is paid to biopesticides to control CSFB have received. Biopesticides serve as a pest control option. They cause a minimal environmental impact, are specific to the target pest and can be a tool for resistance management [10, 40].

Oilseed rape is particularly vulnerable to pest damage at the early stages of growth. And it is far more tolerant to attack after the cotyledons have unfolded. The need for treatment can be determined by the number of shot-holing symptoms, leaf area eaten by beetles (**Figure 3**) or larvae and the plant's growth rate. Along with the adult beetle harm, the autumn, winter and spring CSFB larval assessment in leaf petioles and stem is present. It needs to be highlighted that the larval damage may be more economically harmful. Autumn larvae are more damaging, as their consumption of plant material last longer, and winter and spring larval invasion is likely to be less significant. If the risk is high –treatment at the first sign of attack is recommended to

Figure 3.
CSFB holing symptoms in oilseed rape.

be considered at the initial stages of growth. For the latter growth stages, such fields should be set up with traps, and the number of pests should be monitored not to exceed [1, 4, 6].

Effective chemistry is considered the best CSFB management option, however, no individual chemical or non-chemical approach is absolutely warranted. Thus, a combination of techniques is recommended for CSFB population suppression. Several alternative methods need to be mentioned. It is important not to damage natural enemy populations, e.g., ground beetles and parasitic wasps, by pesticide applications (especially broad-spectrum pyrethroids) and intensive cultivation. Great benefits were obtained in trials with trap crops. This approach uses trap crops to attract CSFB and simultaneously divert it away from oilseed rape. Afterwards, CSFB eggs or larvae die when the trap crop is destroyed. The disadvantages of this approach are that the use of relatively large areas of trap crops (at least 2 ha) is recommended and that the benefits can be variable. However, the trial approaches showed up to 88% reduced adult CSFB infestation and 76% reduced oilseed rape damage. It is recommended for a trap crop to be at an early growth stage at the end of August. This could make it more attractive to CSFB [40–42].

As an alternative solution, the selection of cultivars is recommended. The susceptibility or attractiveness of different varieties to CSFB has not been evidenced. Nevertheless, it is recommended to choose hardy varieties in the context of CSFB control. Such varieties can reach the four-leaf stage faster. This property makes the plant more tolerant to CSFB adult and larvae feeding damage [3, 4].

The maintenance of optimal soil humidity during crop germination is essential. Aiming to provide sufficient moisture levels, sowing dates should be adjusted regarding the soil humidity level and weather conditions and forecast. In addition to maintaining soil humidity and enriching the soil with organic matter, the cereal stubble and straw also have several benefits of their presence in the field for CSFB management. It is suggested that stubble and straw make it difficult for CSFB to locate the germinating oilseed rape and are useful as a support for spider web [1, 5].

The date of sowing is also shown to play a vital role in the CSFB management. Avoiding the alignment between beetle migration peak and the most susceptible crop growth stages is recommended. The sowing period of the highest risk from adult CSFB lasts from the end of August to early September. The early sowing ensures successful oilseed rape germination and establishment before the CSFB migration. The late sowing reduces an adult CSFB beetle feeding damage by moving the germination after the migration peak and reducing the larval invasion by slowed egg laying and development under cooler conditions. Studies have shown that a 10-fold reduction in larval invasion is obtained by a three-week postponement of sowing.

The optimisation of seedling density can also be used to reduce the risk of CSFB damage. To achieve final optimal plant density under the threat of CSFB invasion, the seed rate needs to be increased. And on the other hand, by decreasing the seed rate, plants may grow larger and more tolerant of larval feeding in the spring [6, 34].

Companion crop species are known to prevent or lessen crop damage by attracting the pest, improving soil, masking the crop from pests, or offering shelter for natural enemies. For example, mustards act as sacrificial plants that are eaten first. The research on CSFB management has detected significantly lower damage in two-leaf and five-leaf stage oilseed rape cultivated with a list of companion crop species. Buckwheat, legumes and *Brassicaceae* family members are known to play a preventing role in CSFB management. The companion crop should be sown about a week before oilseed rape and can be removed by frost or by the herbicide. It should also not outcompete oilseed rape [3, 7, 41].

As CSFB larvae generally settle in leaf petioles, trials have shown that managed defoliation reduces larval invasion by up to 55%. It has also been found that sheep grazing and topping/flailing are effective in reducing larval populations. The most beneficial is late defoliation before stem extension (November and December). Later defoliation could be dangerous due to a lack of time for plants to recover. It is also suggested that CSFB damage could also be reduced by the addition of organic amendments during the establishment period. The use of organic amendments may be helpful to for CSFB invasion management by improving plant growth, masking the crop, and repelling the pest. Moreover, crop tolerance to larval damage can also be enhanced by proper nutrition and plant growth regulation. It should be noted that the management tools proposed to control the CSFB spread are also useful in eliminating many other issues in oilseed rape cultivation [12, 40].

7. Oilseed rape breeding

Breeding is an excellent tool for improving many crops' preferred characteristics. The most common desirable traits usually are higher yield, resistance to stress and diseases, and improvement of specific characteristics of the plant. Breeding is a time and resource-consuming technique. The process of cultivar development, starting with initial crosses and finishing with commercial registration, takes about 10 years. Many advances have been achieved in oilseed rape improvement due to the collaborative effort of plant breeders, pathologists, physiologists, agronomists, and other specialists. These efforts reduced production risks for farmers who grow these cultivars and resulted in greater seed yield, modified content of seeds, earlier maturity, disease, and pod shatter tolerance [1, 4].

Crosses are made between perspective genetic material and selected for desirable seed yield, the presence and content of seed components, e.g., specific amino and fatty acids, oil, protein etc. During the oilseed rape breeding history, the contents of unwanted compounds found in the oil, such as erucic acid and glucosinolates, were significantly decreased to ensure safe use for edible purposes. Moreover, the oil content, seed yield, and disease resistance have also significantly improved. Knowledge about the relationships between closely related species is essential for plant breeders. It is an excellent source of genetic material for developing new cultivars. There is a significant number of created winter and spring oilseed rape cultivars. They are sorted according to their characteristics [1, 12, 23].

HO and LL (high oleic and low linolenic fatty acid content) cultivars, due to the modified contents of oleic and linolenic fatty acids, are healthier for human health. The stable oil of HO and LL varieties benefits the food processing industry [7, 15, 43].

LEAR (low erucic acid oilseed rape) development started in 1960, when oilseed rape plants with low eicosenoic and erucic acid contents were isolated by Canadian breeders after the high eicosenoic and erucic fatty acid contents were questioned. Soon, in 1967, seeds of cultivar 'Bronowski' were found to have a low content of glucosinolates. This genetic source of low concentration of glucosinolates was then used to develop cultivars with low levels of erucic acid and glucosinolates ("double low" cultivars). Multiple improvements of oilseed rape cultivars throughout the breeding process dramatically reduced erucic acid levels. These cultivars are used for edible oil production. The current standard requirement for these cultivars is less than 2% of erucic acid in the fatty acid profile and less than 30 micromoles of any one or a mixture of the glucosinolates (3-butenyl glucosinolate, 4-pentenyl glucosinolate, 2-hydroxy-3 butenyl glucosinolate, and 2-hydroxy- 4-pentenyl glucosinolate) per gram of air dry and oil-free solid. The reduction of the content of glucosinolates expanded the use of oilseed rape meals in animal husbandry [1, 3, 7, 16].

HEAR cultivars were developed for non-edible purposes. They are commonly grown for industrial use. HEAR cultivars are used to produce lubricants, plastics, lacquers, and detergents. Reducing the levels of glucosinolates enabled the usage of HEAR cultivars as livestock feed [5, 23].

The characteristics of oilseed rape can also be modified by hybrid seed production. An oilseed rape hybrid results from crossbreeding two oilseed rape lines. And the more distant the parents, the greater the hybrid power. It was observed that hand crosses between two distant lines of oilseed rape result in up to 45 per cent higher seed yield than in parent lines. It was shown that oilseed rape hybrids have higher stability, disease resistance, and yield. However, the by-hand method is time and source-consuming and thus hardly possible at a large scale. Since oilseed rape cultivars are mostly self-pollinated thus, self-pollination of parental lines must be controlled during the hybrid creation process. Therefore, several approaches have been developed to produce oilseed rape hybrids [7, 12].

One of the developed hybridisation systems is the cytoplasmic male sterility (CMS) system. The first commercial CMS oilseed rape hybrid was registered in 1989. Its use enables oilseed rape breeders to produce female plants that either do not produce pollen, do not shed pollen or make pollen that cannot cause self-fertilisation. Its use allows canola breeders to grow female plants that either fail to produce pollen, do not shed pollen, or which pollen cannot self-fertilise. This system was invented after discovering that some *Brassica* species have male-sterile cytoplasm. Fertility is determined by an interaction of the nucleus and cytoplasm. A mutation in certain cytoplasmic bodies disables the development of functional pollens or anthers [3–5].

The hybrid system usually consists of three lines: a male sterile, a maintainer and a restorer line. The male sterile female plant flowers have a sterile cytoplasm due to the gene isolated from the soil bacterium and inserted into this line. The inserted gene controls the production of the particular enzyme in the specific cell layer. It disables the development of pollen. Thus, these plants cannot self-pollinate. These flowers are crossed with the genetically identical maintainer line, which produces pollen. This line contains another gene obtained from the same soil bacterium. This gene has an inhibitor enzyme that counteracts the sterility enzyme in the male sterile line to restore fertility. The obtained seeds maintain CMS characteristics. The restorer line is genetically different from the male sterile line. It contains genes that compensate for the cytoplasm gap and restores fertility in the hybrid. The 100 per cent hybrids are obtained by inserting the target gene into both parental lines. A hybrid tolerant to the herbicide glufosinate ammonium was developed using this kind of breeding technique [5, 44].

The other breeding method is the production of “synthetic” cultivars. It exploits the heterosis present in the Brassica family. Synthetic oilseed rape cultivars are developed by mixing seeds from two or more parental lines from two lines and by growing out the mixed seed to produce certified synthetic seed. The synthetic seed, including hybrid and parental plants, is more stable under various environmental conditions than conventional cultivars. The degree of outcrossing depends on the insect pollination degree; thus, it is unpredictable. A mixture of the parental lines and all possible hybrids between them will be obtained in the next generation. A list of herbicide-tolerant cultivars has been developed using mutagenesis and gene transfer. These cultivars are tolerant to specific herbicides or their groups. The first triazine-tolerant oilseed rape was registered in 1984 in Canada. It was developed to enable the cultivation of oilseed rape in areas infested with weeds of the *Brassicaceae* family, e.g., wild mustard, stinkweed, and ball mustard. Later, cultivars tolerant to imidazolinone, glyphosate (Roundup), glufosinate ammonium and bromoxynil were developed. It was demonstrated that isogenic lines have different energy use efficiencies under certain growing conditions due to epigenetic differences [1, 5, 45].

8. Future prospects

Nevertheless, much effort has been made in oilseed rape cultivation, breeding, and production improvement. Still, there are issues that need to be solved. The improvements of oilseed rape cultivars should be oriented to enhance the tolerance to the environment, especially for xeric conditions, disease, and herbicides, to eliminate green seed, increase yield, develop early cultivars for short season environments and improve nutrient use efficiency.

Also, an effort should be made to improve cultivars for lodging and pod shatter tolerance. The studies should also be oriented to explore new possibilities to use oilseed rape in producing new biodegradable products, develop sustainable solutions for oilseed rape cultivation, explore beneficial oil extraction methods, and improve pest control management. And finally, the benefits and the harm of oilseed rape use for human health should be better examined.

9. Conclusions

Oilseed rape is a member of the Brassicaceae family. This crop is commonly known as the oilseed rape, rapeseed, canola or colza. It has been grown for thousands of years for its oil content, and currently, it is one of the most commonly used sources of vegetable oil. Oilseed rape oil is used for edible and nonedible (industrial) purposes with various end uses, including fuels and bioproducts. It is also used as a source of protein for food and industrial applications, as a remedy, as an ornamental plant, as a fodder crop, as the source of nectar and pollen, the source for the production of cosmetics and biodegradable products and many other purposes. It is helpful to complete human and animal nutrition and prevent or fight certain diseases. All parts of oilseed rape are useful. Even the waste is used for various needs, e.g. to feed animals, recycle or fertilise the soil [1–3].

Oilseed rape oil is one of the oldest known vegetable oils, however historically, it was used in limited quantities due to high levels of erucic acid, which is damaging to cardiac muscle, and glucosinolates due to antinutritional values and adverse physiological effects when present at above the tolerance level are damaging the thyroid, kidney and liver. During the oilseed rape breeding process, erucic acid and glucosinolate in the seeds have dramatically reduced. In contrast, oil content, seed yield, and disease resistance have been significantly improved. Improved end-use quality has increased the market for oilseed rape seed and its products [19].

Oilseed rape is a very productive oil source. It produces more oil per unit of land area than other oil sources. Its productivity depends on a list of factors. These are the genetic potential, the characteristics of the environment (soil, humidity (water), climatic and biotic conditions) and management strategies (crop sequence, rotation, and tilth options). Also, nevertheless, oilseed rape is a self-pollinating plant;

however, the pollination by bees increases the final yield. Moreover, winter oilseed rape is, on average, 45% more productive than spring oilseed rape [12, 16].

This review summarises the knowledge on oilseed rape importance, prevalence, breeding improvements and the issues of its cultivation and management.

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Conflict of interest

The authors have no conflicts of interest to declare.

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Chapter 2

Processing of Oilseeds in the Tropics: Prospects and Challenges

Theophilus M. Ikegwu, Clement C. Ezegbe, Eunice N. Odo, Chioke A. Okolo, Joy C. Mba and Helen O. Agu

Abstract

Oilseeds have been cultivated from antiquity with increasing demand in agricultural industries world trade. Many economies such as Malaysia depend largely on oilseed crops which are grown primarily for the edible oil production; and for additional meal fraction arising from the seed. The meal is rich in protein and used for animal feed. Recent developments in research have posited oilseeds as a viable source for the production of biodiesel. In the tropics, most of the oilseeds are underutilized; and interest in its mass production and utilization are lacking. Some other seed such as neem seeds, pawpaw seeds, Jatropha curcas L. seeds, etc. have not been put to use in tropical countries leading to subsistence production and their applications in other areas. The oilseed crops could be used either for human, animal or for industrial purposes. There is need to increase the volume of production of these oils in tropical countries through improved quality farming techniques that would encourage breeding in other to meet up with increasing demands. Notably, there are many conventional methods that have been used to increase oilseeds yields. However, the adoption of each technology improvement should be sustainable, while other unknown oilseeds should be discovered for increased utilization.

Keywords: oilseed, peroxidation, antioxidant activity, tropical crops

1. Introduction

Oilseeds are seeds grown all over the world and primarily for the production of edible oils. Tropical oilseeds include almonds, avocado, hazelnut, canola, linseed, flaxseed, coconut, peanut, soybean, oils palm, olive and walnut seeds, among other underutilized ones. They are considered important crops due to their high potentials, functional roles, processing needs and economical value. World production of major oilseeds reached 611.48 million metric tons in 2021–2022 and among oilseeds soybean is the leading type (363.86 million metric tons) followed by rapeseed (70.62 million metric tons), sunflower seeds (57.26 million metric tons), groundnut (50.68 million metric tons), cotton seed (43.50 million metric tons) and palm kernel (19.73 million metric tons) [1]. Oilseeds are rich in oleochemicals, phytochemicals such as flavonoids, tocopherols, phenolic compounds, lignans, tocotrienols, protein, fat, ash, fiber, carbohydrate, vitamins, minerals and some antinutritional factors like glucosinolates and phytates [2, 3]. The oilseeds have great potentials in the future both in the economy of the producing nation and in the food value chain. Interestingly, the tropical climate supports diverse species and varieties of oilseed crops production, but is, however, hampered by the traditional processing technologies (**Figure 1**) of the different countries which make its production and processing drudgery and less attractive to young ones. Additionally, absence of adequate conservation technology for the locally sourced oilseeds prior to processing is a major constraint to its export potentials. To avoid postharvest losses of up to 50% of the oilseeds, large-scale industrial processing operations are required to meet the quality criterion in the market [4]. Notably, some tropical countries such as Malaysia, India and Thailand have braced the odds and are ranked among the world oilseed producing nations whose contribution their gross domestic products (GDP) is very high.

Processing of oilseeds is designed to achieve high extraction yields, obtain high quality oil with minimal undesirable components and produce high value meal. Recently, due to increasing world population, demand for high-quality healthy vegetable oils continues to increase for human diet, domestic and industrial applications.

Oilseed processing industry in the tropics has faced some challenges which led to widespread inefficiency which affects domestic markets and export quality such as use of local technologies, the lack of modernization, low oil recoveries, lack of standardization of product quality among small-scale processors [5, 6]. Despite the several challenges, the sector has massive potential for tremendous growth if various governments introduce special investment incentives for investors and for regulators to monitor and enforce environmental controls and standards. This book chapter is aimed at utilization potentials of oilseeds in the tropics, therapeutic considerations, source of vital nutrients for consumers, prospects, and challenges of oilseed production for increased global competitiveness.

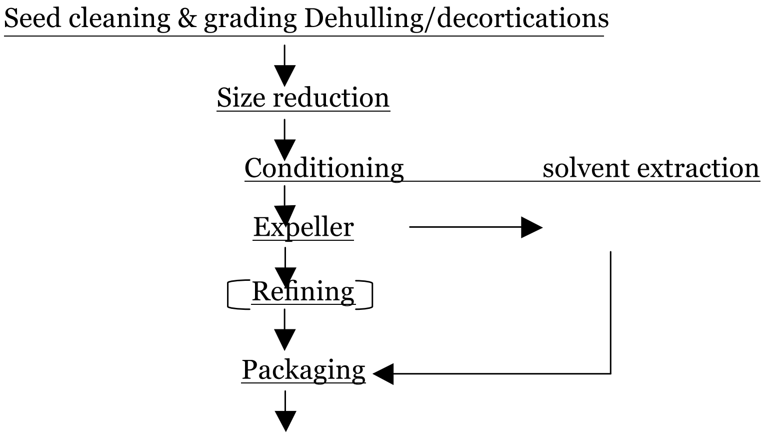

Figure 1.
Traditional oilseed processing technology flowchart.

2. Utilization potentials of tropical oilseeds

Many varieties of oilseeds in the tropics particularly, palm kernels, groundnut, sunflower seed, soybean castor seed etc. are some of the sources of the edible oil. The edible oil is the main source of fat taken in daily meals in different developing countries in the tropics and is used for various purposes. Oilseeds are made up of particles called cells while oil glands are embedded in each of the cells which liberate oil from rupturing. Hence, the essence of oilseed processing is to rupture the gland and cell wall which gives a yield of oil by application of heat and pressure during flaking, followed by extraction. The oil extraction processes are designed to achieve high extraction yields, produce value meal/cake and obtain high-quality oil with minimal undesirable components [7]. There are several techniques for extracting oil from oilseeds. However, mechanical extraction using a screw press and solvent extraction are the two common oilseed extraction processes (**Figure 1**).

2.1 Preparation, handling and storage

The physical properties of the seeds, such as bulk density, shape, size and flowability affect the design of oilseed facilities. Typically, in the tropics oilseeds are cleaned and sorted to remove stones, sand, dust, leaves and other contaminants after harvest and before storage. Proper handling and storage of oil-containing materials are vital so as to minimize deterioration and as well as maintain a good quality of both contained oil and meal. All oil-bearing needs to have correct moisture content to maximize the oil yields as the high moisture content in seeds has an adverse effect on oil and meal quality. Whole and low-moisture oilseeds of about 8–10% may be stored for an extended time under suitable conditions [8].

2.2 Unit operations for oilseeds processing

Although most oilseeds go through pretreatment processes for oil extraction as shown in **Figure 2**, however, the unit operations vary slightly depending on the oil content and physical properties.

Cleaning: Oilseeds may contain certain impurities from the field, during storage and or entered on transit. Such impurities include plant stems, leaves, sticks, infected seeds, dust, stones, foreign material etc. Impurities and foreign materials in the seeds are removed by the use of screens, reels, aspiration or separated by gravity.

Cracking: Most oilseeds are reduced in size to facilitate other downstream processes such as drying, dehulling, tempering and flaking prior to oil extraction. Cracking mills are used for seed size reduction.

Drying: The moisture content of oilseeds is reduced so as to improve the effectiveness of downstream processing particularly, dehulling and tempering.

Dehulling: The husk or shell needs to be separated from the oilseeds prior to oil extraction and the amount of hull on the oilseeds varies significantly. Thus, dehulling increases oil production efficiency and its efficiency is measured by the residual fiber content in the meal and the residual oil content in the hulls.

Tempering: This is done to facilitate oil recovery by heating to about 90°C in order to denature the proteins, release oil from the cells and inactivate enzymes. It is important to maintain the optimum temperature to avoid the formation of undesirable

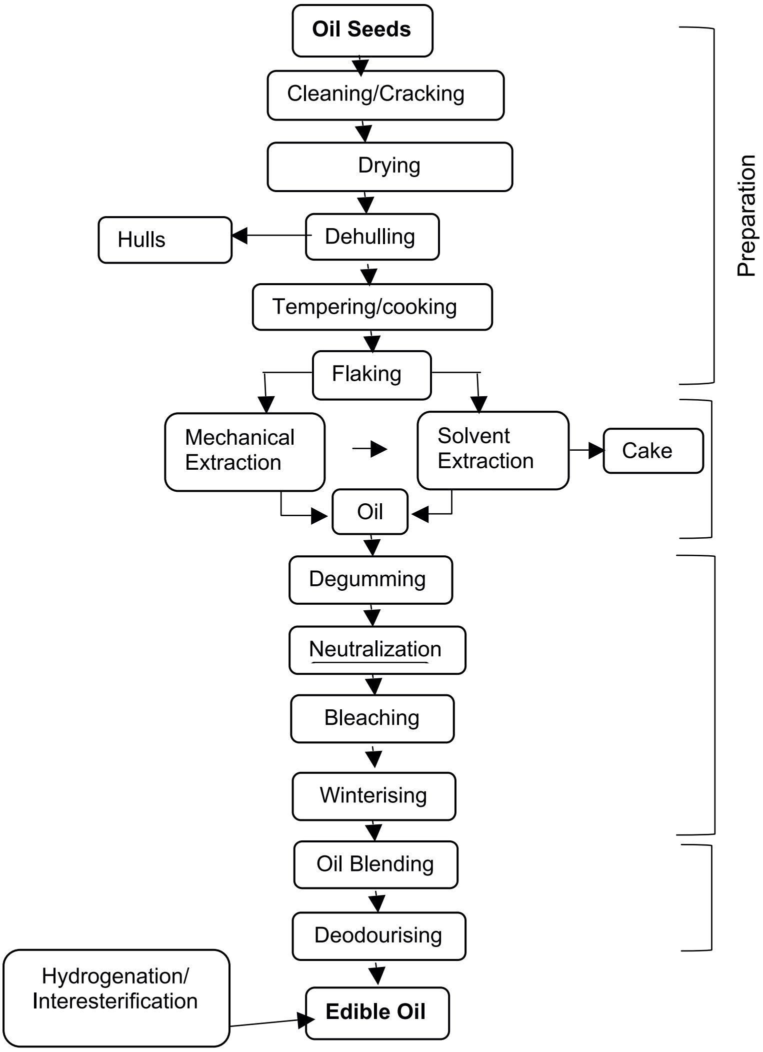

Figure 2.
Processing of oilseeds into edible oil.

aromas and coloring compounds. Tempering improves extraction efficiency and flaking performance. The seeds are then pressed to separate oil.

Flaking: It involves rupturing of the seed cellular structure while increasing the surface area for increased contact between seed and solvent during the solvent extraction process. It is important to note in order to minimize meal and oil quality deterioration, the oil from the flaked seeds should be extracted within 24 hours after flaking.

Extraction: This is the process of separating a liquid from a solid system by either pressing or with the use of a solvent. Although a good percentage of oil is removed by pressing, however, extraction using a low boiling point solvent gives a higher recovery of oil and drier cake than expression. Solvent extraction removes nearly all available oil from oilseed meals. The process provides meals with higher protein qualities and better preservation qualities.

i. **Mechanical Expression:** This is a process of pressing liquid out of liquid containing solids. The oilseeds are compressed in various types of compression devices and the recovery of the oil varies depending upon the sizes and seed being pressed. The oil is removed by pressure from a screw press or an expeller. As the pressure increases, the material is compressed and oil is expelled. It is however more economical to apply lower pressures and then remove the remaining oil by a solvent extraction process.

ii. **Solvent Extraction:** The extraction of the flaked material is performed using non-polar solvents such as food-grade hexane having a boiling point of 65.5°C. The oil is separated from the mixture of oil and hexane called miscella by distillation and stripping under a vacuum. The oil-free flakes are desolventized that is steamed to remove the solvent and dried, cooled and sold as protein-rich feed for cattle. The crude oil obtained contains suspended substances or impurities which are removed by filtration.

iii. **Degumming:** This is a process of removing phosphatides by hydration with water and they vary from one to another and even in the same kind of oils. The phosphatide which makes a gummy residue must be removed to prevent the darkening of the oil during the high temperatures of deodourization and in later applications like frying and to extend oil shelf-life. By mixing the oil with 2–3% water, the hydrated phosphatide can then be removed by settling, filtering or centrifuging. There are two types of phospholipids; hydratable and non-hydratable phospholipids. The non-hydratable phospholipids can be eliminated by the action of strong acids such as citric and phosphoric acids. The strong acids are used to chelate and withdraw the divalent cations and restore phosphatide solubility in water and these can then be eliminated.

iv. **Neutralization:** Any free fatty acids, pigments, waxes and phospholipids in the extracted oil promote fat oxidation and lead to undesirable colors in the final products. These impurities are removed by treating the oil with sodium hydroxide. However, two refining systems are used; short mix process and long mix process. The short mix process is conducted at 90°C using more concentrated sodium hydroxide and a mixing and centrifuging time of less than 1 minute. While the long mix process is conducted at 33°C using lower concentrated sodium hydroxide and mixing and centrifuging time of about 8–15 minutes [9]. The refined oil is lighter in color, less viscous, and more susceptible to oxidation.

v. **Bleaching:** Before the oil is sent for further treatment, various contaminants, pigments, metals and oxidation products are removed. The appearance of the oil can be lightened by bleaching and the types of bleaching material include activated carbon, acid-activated earth and natural earth.

vi. **Winterization:** This is a process of removing glycerides/waxes so as to obtain clarity of oil. In this process, oil is crystallized at a lower temperature, and the glycerides/waxes become solidified and are removed from the oil by filtration.

vii. **Hydrogenation/Interesterification:** The process of adding hydrogen to saturate the carbon-to-carbon double bond is known as hydrogenation. It is used in order to increase the stability against oxidation while raising triglyceride melting points.

On the other hand, interesterification is a technique for positioning or rearranging fatty acids on triglycerides. This technique is followed as a means of obtaining trans-free margarine, spreads, and shortenings since controversies exist about the healthfulness of trans-fatty acids produced during hydrogenation.

viii. **Oil Blending:** This is an optional unit operation in the processing of oilseeds into edible oils. It is used primarily when oils with specific solid temperatures profile are prepared. However, if oil blending does not occur, the oil may go directly from bleaching to deodourisation.

ix. **Deodourization:** This is a process of applying high-temperature steam but at low pressure in order to remove undesirable odorous compounds by sparging process. Odor, flavor and stability are essential compounds of oil. After deodourization, the oil is packaged in polyethene in the form of low-density-polyethene (LDPE) coated paperboard/aluminum foil laminates. Packaging directly influences the quality of the oil by protecting the product from both light and oxygen.

3. Industrial applications of oilseeds

3.1 Soybean oil

The secondary components of soybean oil are valuable commercial products. They include lecithin, phytosterols and tocopherol. Lecithin is produced by degumming soybeans and is the predominant source of food emulsifiers. In the food industries, soybean oil found its application in the following:

1. Shortenings and margarines:

    - Cake making: Soy-based shortenings and margarines used in cake making are very effective in preventing formation of a gluten matrix in cakes, which results in cakes that are pleasingly light, airy and moist. Cakes produced with these shortenings and margarines have very favorable texture characteristics and optimum dome height.

    - Cookies madding: soy-based oils and shortenings produce a favorable spread, height and weight along with a tender mouthfeel in cookies.

    - Icing making: Soy-based oils and shortenings produce icings with an ideal viscosity and specific gravity. High oleic soybean shortening can increase the volume of icing which means more frosting is produced with fewer products.

    - Pies: Soy-based shortenings produce pie crusts with desired characteristics, including evenly browned textured, flaky crust with an ideal finished product height and minimal shrink.

2. Release agent: A blend of soybean oil with soybean lecithin provides excellent release properties, enabling easy removal from baking utensils and conveyors. Reduced sticking makes for easier clean up and better product integrity.

3. Bread making: Less elasticity, better texture, more tender and fluffy breads, are achieved when using soybean oils in dough. Higher levels of soybean oil in specialty breads such as brioche and dinner rolls will reduce chewiness and toughness while contributing to a delectably crispy crust.

4. Deep frying: With lower levels of polymerization, high oleic soybean oil can lead to cost savings due to reduced build-up of polymers on equipment when deep frying. High oleic soybean oil was a top performer on overall likability in a fry taste test which evaluated flavor, aroma, texture and appearance.

5. Packaged foods: High oleic soybean oil offers superior resistance to oxidation, which extends shelf life of packaged products, as well as a desired neutral flavor profile, allowing the natural flavors of ingredients to stand out.

6. Fried snacks: With its neutral flavor profile and high level of oxidative stability, high oleic soybean oil is the ideal frying medium for snacks of all types. Because of its high stability, longer fry life and better frying efficiency will result when using high oleic soybean oil.

3.1.1 Non-food industrial application of soybean oil

These include manufacture of caulks and mastics useful as adhesives or sealants. These adhesives and sealants are commonly used in a variety of high moisture applications including bathroom and basement waterproofing. The use of soybean oil in these sealants ensures they are pliable and flexible enough for bonding and repairs. Soybean oil is also valuable in soap and candle making, especially as a mold release agent. In soap making, soybean oil produces neutral effects and poses no potential skin problems. It's also an inexpensive release agent that does not compromise quality or consistency. According to studies by the USDA-ARS Oil Chemical Research Unit, soybean oil can serve as a significant substitute for the petroleum-based resin needed to make parts for automobiles and other types of equipment.

3.2 Sesame seeds oil

The antioxidant properties of refined sesame seed oil allows for greater shelf life with improved flavor and taste for use in the food industry. Roasted sesame oil resists rancidity due to the antioxidants formed during seed roasting and the particular roasted sesame add flavorand improves taste of fried products. Extra virgin sesame seed oil is used for salad dressing and cooking. Refined sesame seed oil is used for food frying, confections such as candy, margarine and baking. Toasted sesame seed oil is used for frying because it burns easily instead added as a flavoring agent in the last stage of cooking. Food products such as sauces and pickles use sesame oil as a preservative to increase their shelf life.

3.2.1 Non-food industrial uses of sesames seed oil

Refined Sesame oil is used as a solvent, oleaginous vehicle for drugs, skin softener, and hair oil; and used in the manufacture of soap [10]. While, Extra virgin sesame seed oil is used for therapeutical massage.

3.3 Canola seed oil

Heart-healthy consumers' value cholesterol-free canola oil for its high percentage of unsaturated fat; the polyunsaturated fats in canola oil are healthy omega-3 and omega-6 fatty acids. It is used for cooking and its high-smoke point is advantageous when deep frying or cooking over extreme temperatures. Canola oil is a traditional ingredient in many salad dressings, shortenings and margarine, cooking sprays, coffee creamers and whiteners, and breads and crackers.

3.3.1 Non-food industrial application of canola oil

It is used to produce fertilizer, pesticides, cosmetics (Lip glosses and lipsticks, creams and lotions (including suntan lotion), toothpastes, soaps, and shampoos frequently contain canola oil as an ingredient to allow products to flow easily as the natural vitamin E in canola oil protects and repairs damaged cells), essential oil (massage oil), biodiesel and lubricants.

3.4 Coconut seed oil

Studies are also being conducted on the feasibility of using coconut oil to synthesize edible packaging material as an additive for starch-based films in food packaging as an improved edible film, for cooking, Confectioners and bakers use refined coconut oil in products that may stand for a time after manufacturing. The oil also has a high smoke point, which allows foods to be fried or sauteed at high heat. Coconut oil is used as a component of infant milk powders because of its easy digestibility and stable flavor. Coconut oil is extensively used in the food industries as a confectionery fat particularly in the preparation of ice creams. In imitation chocolates coconut oil is used in place of cocoa butter along with cocoa powder.

3.4.1 Non-food industrial application of coconut oil

Coconut oil has found application as a health care product for preterm infants in their skin maturation development. Results of studies conducted on many new-borns under randomized controlled conditions showed that coconut oil has beneficial effects on new-born health and has no undesirable side effects. Coconut oil also has antibacterial properties. Researchers have reported that the antibacterial properties of detergents could be greatly improved by replacing the surfactant used in the manufacture of detergents with new surfactants derived from coconut oil.

Coconut oil can be a potential feedstock for biodiesel production. With the help of cellulose-Zn/SiO_2 nanocomposites, biodiesel methyl esters of coconut oil can be formed more efficiently, which further promises that coconut oil could also be used in the fuel industry. Also, coconut oil could be combined with soot to develop a strain sensor. This strain sensor can be used for various applications such as human activity detection, health advice, as well as soft robotics. Coconut oil is also used in industry to make cutting fluids and lubricants. However, this application is limited by its poor thermal stability due to its poor thermal stability.

3.5 Corn seed oil

Corn oil is used as a salad oil, for frying and margarine making because it contains little cholesterol.

3.5.1 Non-food industrial application of Corn oil

It is used for making soaps, paints, insecticides, biodiesel and inks.

3.6 Olive seed oil

Pure olive oil is used mainly for culinary purposes and in the preservation of foods, mostly canned fish.

3.6.1 Non-food industrial application of olive seed oil

It is also used in the textile industry for wool combing, for toilet preparations and cosmetics, in the production of high-quality castile soap, and as a lubricant.

3.7 Walnut seed oil

It is used for various cooking purposes because it has rich, nutty taste and been proved to reduce high blood sugar and cholesterol level.

3.7.1 Non-food industrial application of walnut seed oil

It is used in the manufacturing of skin care products, hair oil and wood finishing oil.

3.8 Hempseed oil

It is used for cooking and topping salads because of its high nutritious and nutty flavor attributes.

3.9 Non-food industrial application

Hemp is used to make rope, textiles, clothing, shoes, paper, bioplastics, insulators, and biofuel.

3.10 Palm oil

For edible applications, Palm oil is currently used extensively in food preparation and manufacturing around the world. When refined, palm oil is used in the food industry as margarine, shortening, vanaspati, sugar confectionary, frying fat and special fat. Recently, it has been used in emulsion based, powdered and convenience food products. Palm oil and palm kernel oil have been used to replace butterfat in ice cream and in milk preparation to make filled milk. Infant formulas as well as salad oils are now being made with palm oil as it has a low melting point. Palm oil has also been used in the pharmaceutical industry as many important oil fractions such as natural carotenes, vitamin E, sterols, squalene, coenzymes and phenolic compounds are used for many pharmaceutical applications.

3.10.1 Non-edible applications of palm oil

This is mainly found in the soap and oleochemical industries, where it is applied in the manufacture of soap, diesel substitute, epoxidized palm oil, polyols, polyurethanes, polyacrylates and raw materials for oleochemicals such as oleochemicals or derivatives based on C12-C14 and C16-C18 chain lengths with a variety of applications. Palm oil has also been used to make rubber, glycerine, soap, candles, and cosmetics.

3.11 Cottonseed oil

Cottonseed oil is used as liquid oil and in the manufacture of shortening and margarine in food industries.

3.11.1 Non-food industrial application of cotton seed oil

It can also be used in the manufacture of soap, sulfonated lubricating oil, pharmaceuticals, rubber, as a carrier for nickel catalysts, and to a lesser extent in the manufacture of leather, textiles, printing ink, polishes, synthetic plastics, and resins. Cottonseed oil has been used in the synthesis of sucrose polyesters as a noncaloric fat substitute, bearing the trade name Olean or a common name Olestra, suitable for human consumption.

4. Nutritional composition and consumption of tropical oilseeds

The oilseeds have great potentials in human nutritional requirements in diets due to its array of proteins, minerals and oils (essential and non essential oils) with huge functional benefits. The nutritional composition of each oilseed, and amino profile differ according to the maturity, type, variety, specie, breeding condition, environment as well as the management objectives [11–13]. It has been reported that oilseeds are currently used essentially for oil extraction for vegetable oils whose characteristic quality is dependent on the composition of the fatty acids. Researchers [14, 15] have identified ome-6 fatty acids in corn, nuts, soybean, safflower, sunflower, among other oilseeds, which have scientifically proven to impact human health and prevent cardiovascular ailments. Apart from human uses, wastes from oilseeds called meals or press-cakes could be utilized for the production of animal feeds. In the traditional society, oilseeds are mainly consumed as intact food grains, or processed into cakes, e.g. groundnut cakes, chifko, etc. [16] (**Table 1**).

The nutritional composition of oilseeds ex-rays the different compositional values of oilseeds in terms of the proximate, fatty acid, amino acid profile, vitamin, steroids, and mineral contents; including such properties of the oils like melting point, refractive index, iodine value, peroxide value, *p*-anisidine value, acid value, saponification value, and the oxidative stability of the oils (**Table 2**, **Figure 3**).

Increased demand for oilseed crops both for domestic and industrial applications has increased recently partly due to the functional roles played by the oilseed, livestock needs and in part, due to population increase and processing needs [18]. According to World Population Review [19], the current world population of estimate as of 2019 is 7.9 billion and is projected to reach about 9.9 billion in 2050. To meet the demand of the growing population, high yielding varieties are been produced through genetic engineering, especially in the area of soybean and oil palm seedlings, not only for the oils they supplies, but also for their cake [20]. Although temperate regions constitutes the major oilseed producers, the tropical regions such as parts of USA, Africa, Malaysia, Indonesia, among other countries contributes about 6% of

Oilseeds/Proximate composition	**Moisture (g/100 g)**	**Protein (g/100 g)**	**Crude fat (g/100 g)**	**Carbohydrate (g/100 g)**	**Ash (g/100 g)**	**fiber (g/100 g) NSP**	**Energy (Kcal/KJ)**
Lanneakerstingii seeds*	3.61	26.39	57.85	10.07	2.08		
Cotton seed kernel**		32.6	36.3	21.9		5.5	506/2117
Lin seed/flax seed**		19.5	34.0	34.3		27.9	492/2059
Peanut (plain)**		25.6	46.0	12.5		6.2	563/2337
Rape seed**		22.0	N	8.3		7.2 (Crude fiber)	452/1900
Sesameseed**		18.2	58.0	0.9		7.9	598/2470
Soya (boiled in unsalted water)**		14.0	7.3	5.1		6.1	141/590
Safflower seed**		16.2	38.5	34.3		N	517/2163
Sunflowerseed**		19.8	47.5	18.6		6.0	581/2410
Olives (in brine)**		0.9	11	Tr		2.9	103/422

**Ouilly et al. [17].*
***McKevith [18].*

Table 1.
Proximate compositions of oilseeds.

Oilseeds/Minerals	K (mg)	Mg (mg)	Ca (mg)	Zn	Fe	Na (mg)	Folate (µg)	Ph (mg)
Lanneakerstingii seeds (mg/kg)*	674.18	317.15	78.33	6.34	4.46	2.48	ND	ND
Cotton seed kernel**	1350	440	100	6	5.4	25	233	800
Lin seed/flax seed**	681	362	199	4.2	6.2	34	278	498
Peanut(plain)**	670	210	60	3.5	2.5	2	110	430
Rape seed**	800	250	400	ND	ND	5	ND	800
Sesameseed**	570	370	670	5.3	10.4	20	97	720
Soya (boiled in unsalted water)**	510	63	83	0.9	3.0	1	54	250
Safflower seed	687	353	78	5.1	4.9	3	160	644

**Ouilly et al. [17].*
***McKevith [18].*

Table 2.
Mineral compositions of oilseeds.

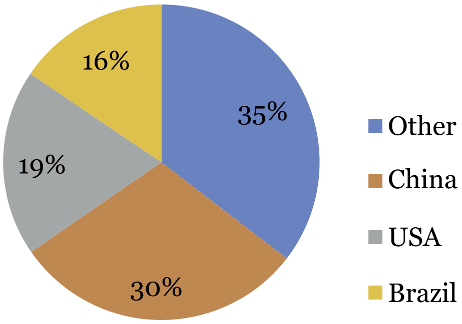

Figure 3.
Global major producers of soybean oil. Source: Shahbandeh [1].

the production, with Malaysia, China and Indonesia as the highest world suppliers of oil palm [16, 21] (**Figure 4**). Other important tropical oilseed crops are groundnut oil, coconut, cotton, neem seed, paw paw seed, etc. Most of the tropical oilseeds are underexploited but very important in traditional folk medicine, especially the oilseeds from the family Anacardiacea, e.g. *Anacardium excelsum*, *Anacardium giganteum*, *Anacardium spruceanum, Anacardium humile*, *Anacardium occidentale* as well as other lesser known oilseeds such as *Lannea microcarpa, Pistacia vera* L. and *Sclerocaryabirrea* (A. Rich.) Hochst [22] (**Figure 5**).

Indonesia and Malaysia produced 85% of the world palm oil supply in 2017 with Indonesia supplying about 53% while Malaysia supplied 32%. China majored mainly on the rapeseed and groundnuts and was also the major producer of soybean oil in 2017 with about 30% contribution to the global supply chain [24]. Three tropical countries (Indonesia, Malaysia and Thailand) accounted for approximately 87% of the global palm oil supply in 2017. With the trend in global oilseed supply, it is expected that sunflower oil supply will decline in 2022 due to the Russian-Ukrainian war. Unfortunately, the three major producers of sunflower oil (Ukraine, Russia and Argentina) lies entirely on the temperate region, which will put a heavy demand on

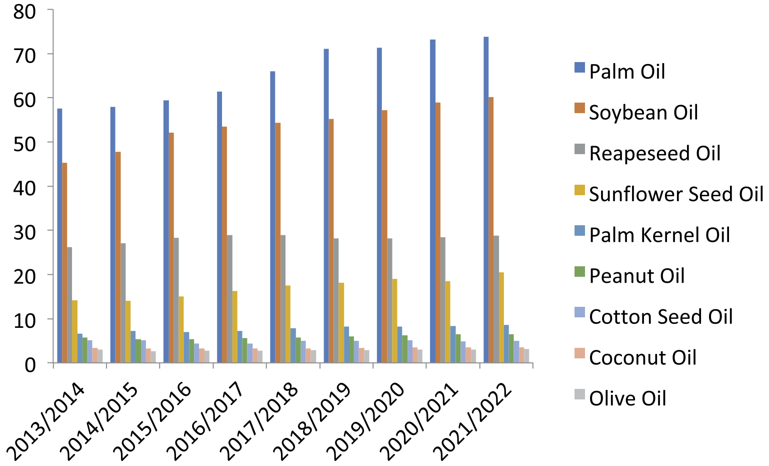

Figure 4.
Consumption of vegetable oils worldwide from 2013 to 2022 (in million metric tons). Source: Shahbandeh [1]. https://www.statista.com/statistics/263978/global-vegetable-oil-production-since-2000-2001/.

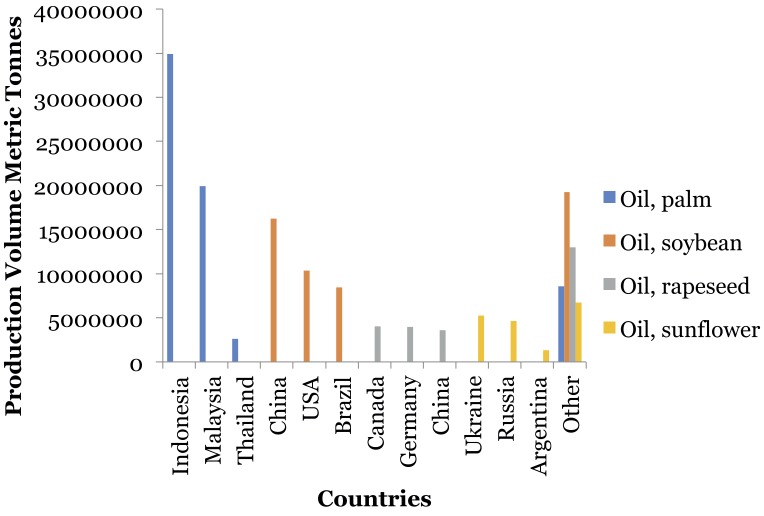

Figure 5.
Source: USDA [23].

sunflower oil from the temperate region. Therefore, the tropical countries could take up this opportunity to improve on their production capacities for increased market demand (**Figure 6**).

4.1 Health implication of oilseed crops

Oilseeds are sources of vegetable oils and fats that provide vital nutritional function in diets, both as a store of energy and as vital component in body nutrition. The oilseeds are sources of vitamin E, fiber, niacin, foliate, iron, phosphorous, and magnesium. The peanuts provide monounsaturated fatty acids, while sunflower and soybean are source of polyunsaturated fatty acids, among others. According to [13], fats and oils contribute more than 39% of the body's calories [17]. The fat may act as

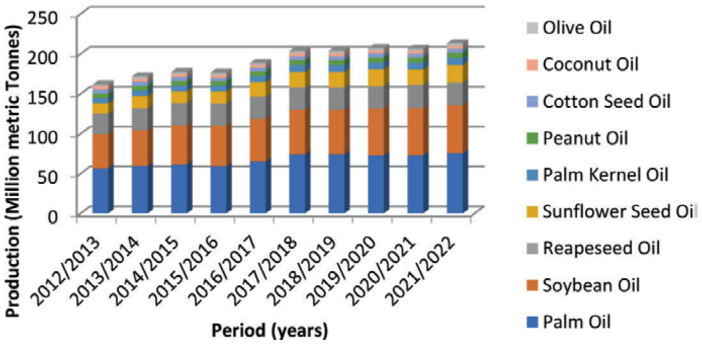

Figure 6.
World production of main vegetable oils by main producers (2012–2022). Source: Shahbandeh [1].

co-factors in vitamin biosynthesis, especially the fat-soluble vitamins, in the supply of essential fatty acids (EFA – our body do not synthesize them but must be obtained from other sources) important in the formation of eicosanoids that serves as signaling substances. It has been established that essential fatty acids, with its associated log-chain derivatives, is important in new tissue formation in the membrane [12]. Essential fatty acids have been associated with brain development, retinal function and nervous system function. Particularly, body fats is an endocrine gland that is involved in the production of signaling molecules for the prevention of fat accumulation in heart, muscles, pancrease, and any other body tissues [25].

The amount of different fatty acids as well as the fat total amount in our food intake greatly influences our health. The emphases on the ratio of the intake of Omega-6 and Omega-3 fatty acids have advocated to be more important than levels of intake of individual fatty acids, although Omega-6 fatty acids have proven to be more vogue due to changing dietary lifestyles [12]. Dietary reference value (DRV) has been recommended for average age brackets in United Kingdom (UK). However, since 1986/87, average intakes of saturated fatty acids has continued to decline in the UK, for men (16.5% food energy) and women (17.17.0% food energy), it was observed vey that intakes still exceeded the Daily Reference Value (DRV) of 11% between 2000 and 2001 survey, suggesting the need for further decrease in the consumption of saturated fatty acids in the UK population. The DRV of fatty acids in developing worlds is still a mirage due to paucity of information in that regard.

It is important to note that excessive consumption of foods with saturated fatty acids and trans fatty acids have been corroborated with increased blood cholesterol levels, a risk factor associated with cardiovascular diseases (CVD). Conversely, the mono unsaturated fatty acids (MUFA) decrease the cholesterol levels responsible for CVD, e.g. low-density-lipoprotein cholesterol (LDL-C). The poly unsaturated fatty acids (PUFA) likewise decrease the LDL-C [1].

The meals from rapeseed, peanut, flaxseed, and soybean are known to provide complete amino acids in diets as they are mixed with other food sources such as cereal grains [17]. Hemp seed oil provides EFA as a cofactor in vitamin assimilation; mustard seed oil could be vital in rheumatoid and arthritic pains (muscle pain). Sawar et al. [17] asserted that the application of mustard oil to scalp enhances hair growth. The health implication of the deficiencies of Omega 3 and Omega 6 fatty acids and the derivatives (prostaglandins) are common and is related to dysfunctional enzyme systems (or genetic disorder) that are immune-system related, as the ratio of consumption of essential fatty acids confers strong immune system and healthy smooth skin. Most of the oilseed crops, tropical oilseeds inclusive, provide adequate supply of vitamin E (antioxidant) carotene, phytosterols, phospholipids, and some minerals such as magnesium, calcium sulfur, potassium, and moderate amounts of zinc, and iron [17]. Rapeseed with about 43% oil and a meal of more than 41% crude protein is therefore an essential oilseed crop due to the array of function performed by protein-rich foods from fatty acid substrates as they acts as hormones, enzymes, tissue structural components, antibodies and as a blood protein [17]. Rapeseed oil are mainly mono unsaturated fatty acids and have been genetically modified to produce cooking oils for food processing applications [26, 27].

Other oilseed crops have been solely used for medicinal purposes, in addition to serving as a traditional culinary spice for ages, e.g. mustard seed (*Brassica juncea*), *cucmeropsismannii, Cucurbita maxima, Cucurbita moschata, Lagenariasicer* aria *and Cucumissativus*. Mustard seeds provide peridoxine (B_6-vitamin), pantothenic acid, thiamin, folates, etc. The vitamin B-complex synthesizes enzymes, aids nervous system function and regulates metabolism in the body [19]. Most oilseeds serve in the development of functional foods and nutraceuticals. Thus, biotechnological research approach through breeding and genetics have been applied in the production of sitostanol enriched soy and canola oils [22].

5. Challenges and prospects

The state of oilseed processing in the tropics leaves much to be desired due to several challenges and large technological gaps which continue to hinder the rapid commercialization of the oilseed processing sector in terms of scale and technology. Although a variety of local technologies are being used in the industry, low utilization of its installed capacity is a challenge. Other challenges include; the lack of modernization in the oilseed processing industry due to inefficient capital machinery, low oil recoveries due to lack of integration between expelling and solvent extraction techniques, lack of standardization of product quality among small-scale processors as most processors produce under non-hygienic conditions without proper monitoring of the quality parameters etc. All this has led to widespread inefficiency in the oilseed processing industry in the tropics which affects domestic markets and export quality.

Furthermore, going by the sustainable development goals of the United Nations, the use of solvent extraction processes in the oilseed processing industry has to take into consideration the health and environmental issues. This in itself is a challenge as alternative and greener solvents have to be used and optimized in the processing of oilseeds while keeping the oil quality intact [28]. Moreover, a sustainable processing methodology and system that has an efficient recovery of the oil fraction from the oilseeds by preserving the quality in an efficient way [29] while eliminating undesirable compounds ought to be adopted.

Nonetheless, despite the several challenges, the sector has massive potential for tremendous growth if various governments introduce special investment incentives for investors and for regulators to monitor and enforce environmental controls and standards. This will lead to the mechanization of bulk handling facilities for enhancing the efficiency of oilseed extractions, development of new value-added products, from the by-products of oilseeds and possibly scientific investigations to machine learning predictive modeling algorithms and simulations for optimization of key parameters necessary to improve oil yield.

6. Conclusion

Processing of oilseeds in the tropics is inevitable because of its high potentials as processed products fetch higher price on sale as compared to the raw materials. There is a need for countries in the tropics to adopt policy reforms and investment strategies that will help oilseed processing in the rural areas particularly, small-scale processors to attain technological advancements, connect to markets and take advantage of any trade opportunities that arise. Thus, sustainable investments in human capital are required so as to scale up to higher-productivity activities in the manufacturing and service sectors.

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Chapter 3

Oilseed *Brassica* Responses and Tolerance to Salt Stress

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Abstract

Salinity interrupts osmoregulation, hinders water uptake, reduces water content, causes ionic toxicity, reduces chlorophyll content, alters stomatal conductance/movement, decreases enzymatic activity, alters transpiration and photosynthesis, disrupts the antioxidant defense system, and results in the oxidative burst. In turn, seed and oil yield is greatly declined. To overcome salinity-induced osmotic and ionic stress, plants evolve avoidance or tolerance mechanisms in order to protect the cellular components from sustaining growth and development. Ion homeostasis, vacuolar compartmentalization, accumulation of secondary metabolites, hormonal regulation, osmolytes production and by activating defensive responses, plants endure the salinity-induced damages, and enhance the stress tolerance. However, these salt-tolerant traits are greatly varied with species and genotypes as well as the extent of salt stress. Therefore, precise studies in understanding the physiology and molecular biology of stress are important to understand *Brassica* oilseed crops' responses and tolerance to salt stress. In this chapter, we summarize the recent findings on the *Brassica* plants' response to salt stress and later discuss the possible ways to enhance salt stress tolerance.

Keywords: abiotic stress, agronomic management, oil crops, osmotic stress, rapeseed, reactive oxygen species

1. Introduction

Soil salinity can commonly be caused by the excess amount of carbonate, bicarbonate, sulfate, and chloride salt of magnesium, calcium, potassium, and sodium. Having a high quantity of adsorbed sodium ions (Na^+) in sodic soil, the soil structure is degraded, for which aeration and water movement are limited [1]. According to the report of FAO [1], more than 424 million hectares of topsoil (0–30 cm) and 833 million hectares of subsoil (30–100 cm) are affected by salinity. Among the salt-affected soil topsoils, 85% are saline, 10% are sodic, and 5% are saline-sodic. On the other hand, 62% are saline among subsoils, 24% are sodic, and 14% are saline-sodic. The data (data on 118 countries covering 73% of the global land area) also represent more than 4.4% of topsoil, and more than 8.7% of the subsoil of the total land area is salt-affected [1]. Saline, sodic, and saline-sodic soils and any other subcategories of salt-affected soils contain too much soluble salts capable of causing an anomaly in various physiological processes in most cultivated plants [2, 3]. Soil salinity primarily provokes osmotic stress by lowering the soil water potentiality, thus reducing water uptake in plants. Whereas another effect of salinization is the imposition of ion toxicity, particularly due to excessive deposition of Na^+ and chloride ions (Cl^-) in the upper part of the plants, and also interferes with the accumulation of essential nutrients [4]. Interference of salt stress in plants is liable for the disruption of metabolic activities such as permeability, biosynthesis of photosynthetic pigments and induces photosystem (PS) inefficiency of plants [5]. Forthcoming salt stress inhibits cell division, hampers cell expansion, alters stomatal closing and opening, reduces turgor pressure, and causes an imbalance in ionic homeostasis [6].

Oxidative stress due to the overgeneration of oxygen radicals and their derivatives, which are called reactive oxygen species (ROS), is the secondary effect of salinity. These ROS could be hydrogen peroxide (H_2O_2), ozone (O_3), singlet oxygen ($^1O_2$), superoxide radicals ($O_2^{\bullet -}$), organic hydroperoxide (ROOH), hydroxyl radicals ($^{\bullet}OH$), perhydroxy radical ($HO_2^{\bullet}$), and peroxyl ($RO_2^{\bullet}$), etc. [7]. The generation of ROS is a general phenomenon of plants in a normal condition to regulate different biological processes such as growth, cell cycle, hormonal regulation, defensive responses against biotic and abiotic stresses, program cell death, and development [6]. But under stressful conditions, excessive generation of ROS leads to oxidative burst and causes damage to cellular components such as carbohydrates, lipids, proteins, and nucleic acids [8]. To combat the adverse effect of this ROS-induced oxidative stress, plants are intrinsically organized with antioxidant defense mechanisms where both non-enzymatic and enzymatic antioxidants work in a coordinated manner to detoxify the over-accumulated ROS. The non-enzymatic antioxidants include flavonoids, carotenoids, vitamins, ascorbate (AsA), and glutathione (GSH), and enzymatic antioxidants are ascorbate peroxidase (APX), monodehydroascorbate reductase (MDHAR), dehydroascorbate reductase (DHAR), glutathione reductase (GR), superoxide dismutase (SOD), catalase (CAT), peroxidase (POD), glutathione *S*-transferase (GST), etc., actively perform their role in quenching the ROS to protect the plants from the oxidative stress [7].

Brassica is placed third among different oilseed species after soybean and palm due to its considerable economic and nutritional value [9]. The genus *Brassica* belongs to Brassicaceae family, which has nearly 435 genera and 3675 species [10]. Having food value and economic importance, plants of *Brassica* genus are well known as edible oil, vegetables, and silage. Rapeseed (*Brassica campestris* L. and *Brassica napus* L.) and mustard (*Brassica juncea* L. [Czern. & Coss.] and *Brassica carinata* A.Br.) are the most cultivated oil-yielding plants of the genus *Brassica*. Europe, as well as North America, cultivates mostly *B. napus* and *B. rapa*. The species *B. carinata* is mostly cultivated in North Africa. *B. juncea* is popular in South Asian countries. *Brassica nigra* (L.) Koch and *B. tournefortii* Gouan are limited to very small area [11, 12]. It is clear that the oilseed *Brassica* plants are cultivated in different continents throughout the world including Europe, America, Asia, and Africa [12]. Studies also prove that salinity is a major problem in different countries of the world, and this salinity is creating difficulties in the proper growth and development of oilseed *Brassica* plants. This plant is more sensitive to salinity in germination, seedling, and reproductive stage. Salinity interrupts osmoregulation, hinders water uptake, reduces water content, causes ionic toxicity, reduces chlorophyll (Chl) content, alters stomatal conductance/movement, decreases enzymatic activity, alters transpiration and photosynthesis, disrupts the antioxidant defense system, and results in the oxidative burst [13–15]. Considering the detrimental effect of salt stress, it is crucial to understand the mechanism of salt-induced damage and tolerance in *Brassica* plants. Inter- and intraspecific differences evidently exist between and among species of Brassicaceae family plants for various stress tolerances including salinity. Their response to salinity and exogenous elicitors under salt stress differs [12, 16]. Understanding all of these is important for enhancing salt tolerance or developing salt-tolerant oilseed *Brassica* plant cultivars. Osmoregulation, hormonal regulation, antioxidant defense, and signaling function are some of the basic strategies that need to be understood for developing salt-tolerant cultivars. Various approaches such as agronomic practices, screening of salt tolerance traits among different *Brassica* plants, traditional breeding, biotechnological approaches, and microbe assistance are some of the approaches practiced for improving salt tolerance capacity of oilseed *Brassica* plants [17–19]. This review presents the previous findings and recent progress in some approaches for the development of salt tolerance in oilseed *Brassica* plants.

2. Salt stress responses in oilseed *Brassica*

2.1 Seed germination and seedling establishment

Poor seed germination, emergence, and seedling growth are among the earliest effects of salt stress on plants [20, 21]. Many pieces of research have revealed that halophytes such as *Suaeda salsa* and *Salicornia europaea* have a strong salt tolerance capacity during the germination stage. However, their germination rates are decreased with increased salinity levels [2, 22], while glycophytes are highly vulnerable to salt stress [23, 24]. Likewise, the salt tolerance capacity of *B. napus* is much lower than the euhalophytes [22, 25, 26]. While screening 549 inbred lines of *B. napus*, Wu et al. [27] found that in the presence of 200 mM NaCl, the seed germination rate of 15 randomly selected inbred lines was decreased.

The seed germination rate and germination percentage (GP) can also be reduced by salinity due to the ionic toxicity and imbalanced nutrient uptake potentiality of plants. Shahzad et al. [19] stated that under saline conditions, *B. napus* showed reduced GP, and the germination rate was slower than normal due to the ionic toxicity or unavailability/reduced nutrient (mainly K^+) uptake ability. According to Damaris et al. [28], the seed germination process is mainly associated with two important enzymes such as α-amylase and protease. Therefore, the seed germination process is hampered due to the reduced activity of these two enzymes under saline conditions [29]. Tan et al. [30] conducted an experiment with 520 *B. napus* germplasms to evaluate their seed GP and germination index (GI) under salt stress and distilled water. There was a large variation seen in both GP and GI values, which were as follows: GP ranging from 26 to 100% and from 0 to 100%, GI ranging from 3 to 54 and from 0 to 25 in distilled water and salt stress, respectively. Another study by Li et al. [31] with canola (*B. napus*) seeds under three levels of salt stress (50, 100, and 150 mM NaCl) stated that seed germination rates were clearly decreased with the increasing levels of salt stress.

Wan et al. [20] experimented with 214 *B. napus* inbreed lines under different levels of NaCl concentration (40, 80, 120, 160, 200, 240, 280, and 320 mM) where the results showed that the germination was inhibited with the increased salt stress levels. Most importantly, a significant variation in germination was observed in 160 mM NaCl solution between different *B. napus* inbred lines. Ahmad et al. [32] observed that *B. napus* seeds germinated slowly after the addition of different NaCl concentrations (50 and 100 mM) into the germination medium. However, under 100 mM NaCl concentration, the germination rate was the lowest with about 30% decrease compared with control condition. The establishment and early growth of seedlings can be both promoted or hampered under salt stress. Fang et al. [33] showed that 25 mM of NaCl solution promoted *B. napus* seedling growth, but the growth was negatively affected with increasing NaCl concentrations (50 and 100 mM).

2.2 Plant growth

Abiotic stressors, such as increasing soil salinity, have been shown to have negative impacts on plant growth and development on many plants [34]. Similarly, the adverse effects of salt stress on the growth and development of oilseed *Brassica* have been widely documented [32]. The plant family Brassicaceae along with the other plants in general shows sensitivity to salt stress that declines the growth and biomass, while retaining a large biomass, indicating tolerance (**Table 1**). Long et al. [46] observed that salinity stress affects *B. napus* root growth at 12-h post-exposure. According to Ashraf et al. [47], increasing salinity slows down cell division and cell elongation because it reduces nutrient absorption, disrupts cell membranes, causes cells to lose their turgidity, and alters hormonal balance, all of which have an impact on plant growth and development. Under 100 and 200 mM NaCl stress, plant growth in terms of the fresh and dry weight of roots and shoots was lowered to a significant degree in *B. napus* plants; however, the reduction was more prominent under 200 mM NaCl [48].

Mohamed et al. [43] showed that salinity affected *B. napus* root system and aboveground growth characteristics significantly. They estimated that the osmotic impact of NaCl stress increases growth inhibitors, decreases growth promoters, and disrupts the water balance of NaCl-stressed plants, which might cause these growth reductions. Salinity reduces some morphological attributes of plants, such as root length, shoot length, root fresh weight, root dry weight, shoot fresh weight, shoot dry weight, leaf number, leaf area, and leaf size. Lei et al. [49] indicated that under 100 mM salinity stress for 144 h, the overall growth rate of *B. napus* seedlings was reduced significantly. Moreover, Wani et al. [50] recorded some alteration in shoot length and leaf area under salt stress by 34% and 47%, respectively.

2.3 Nutrient imbalance

Salinity hampers plants' normal growth environment by altering the nutrient status of the soil. Due to excessive accumulation of Na^+, the uptake of macronutrients, for example, nitrogen (N), phosphorus (P), calcium (Ca), and potassium (K), and micronutrients, for example, zinc (Zn), iron (Fe), manganese (Mn), is affected. However, over-accumulation of Na^+ highly changes the uptake of K^+, causing changes in ion homeostasis and stomatal opening of the plant cells. Na^+ transport is unregulated in most of the salt-sensitive species of oilseed Brassicaceae family [35]. As Na^+ tends to accumulate more quickly to a harmful level than Cl^-, most research has focused on Na^+ exclusion and controlling Na^+ transport within the plant cell [4]. Many of the experiments with the members of oilseed Brassicaceae family showed that salt stress potentially decreased essential macro- and micronutrients uptake. Iqbal et al. [51] experimented with *B. juncea* under 100 mM salt stress, where both the leaf N content and the activity of nitrate reductase (NR) enzyme, related with N-uptake and metabolism, were significantly reduced. Another study from Yousuf et al. [35] found that under 150 mM of NaCl concentration, *B. juncea* showed a

Species and Cultivars	Salinity doses and duration	Responses	Reference
B. juncea cv. CS-54	150 mM NaCl; 10 d	Total biomass accumulation was reduced by 1.69-fold	[35]
B. juncea cv. Pusa Jai Kisan	100 mM NaCl; 15 d	Reduced leaf area (LA) and dry mass	[36]
B. napus cv. Dwarf Essex	100 mM NaCl; once a week	Reduced root and shoot fresh weight (FW) and dry weight (DW)	[37]
B. juncea cv. Pusa Bold	50, 100, 150, 200, 250, 300 mM NaCl; 30 d	Reduced LA, shoot FW and DW, root FW and DW	[38]
B. juncea cvs. CS-52, Pusa Agrani, Pusa Vijay, Pusa Varuna, CS-54, Pusa Jai Kisan, Pusa Bahar, Pusa Kranti, Pusa Bold, Pusa Laxmi, Pusa Basant, ZEM-1, RC-781 and JM-1	50, 100, 150, and 200 mM NaCl; 10 d	Maximum biomass reduction in Pusa Agrani, minimum in CS-54 in a concentration-dependent manner	[39]
B. juncea cv. Varuna	200 mM NaCl; 90 d	Reduced shoot length (SL) by 59%, root length (RL) by 41% and DW by 53%	[40]
B. carinata cvs. Adet and Merawi	50, 100 and 150 mM NaCl; 28 d	Reduced RL (47 and 49%), SL (35 and 38%), leaf number (LN) (20 and 29%), LA (28 and 27%) in Adet and Merawi at 150 mM NaCl, respectively	[41]
B. juncea cvs. Varuna and RH-30	78, 117, and 156 mM NaCl; 60 d	Reduced root FW and DW, shoot FW and DW, LA; Varuna showed more tolerance than RH-30	[42]
B. napus cvs. Yangyoushuang2, Xiangyouza553	100 mM NaCl; until harvesting	Reduced RL (5%), SL (46%), LN (7%), LA (16%), root DW (23%), stem DW (36%) and leaf DW (18%)	[43]
B. juncea	8, and 12 dS m^{-1} NaCl; 5 and 10 d	Reduced growth in a dose-dependent manner	[44]
B. juncea cv. Varuna	50 and 100 mM NaCl; 30 d	Reduced SL (54%), RL (54%), shoot FW (56%), root FW (53%), shoot DW (57%) and root DW (52%)	[15]
B. juncea cv. Varuna	100 mM NaCl; 15 d	LA and plant FW were decreased significantly under salt stress	[45]

Table 1.
Alteration in growth parameters of oilseed Brassica sp. under salt stress.

considerable reduction (1.63-fold) in NR activity than the control plants. Therefore, it is evidently proved that the activity of nitrate influx is substantially reduced under extreme salinity stress.

Under salt stress, total N content in oilseed *Brassica* plant leaves was declined, as did the concentrations of essential micronutrients, such as Fe, Zn, and Mn in the root, stem, and leaves [3]. They did, however, reveal that tolerant genotypes were able to retain higher N and other micronutrient levels when stressed. Also, a comparative study from Singh et al. [52] showed changes in the macronutrient (K, Ca, Mg, P, and S) and micronutrient (B, Fe, Zn, Mn, Cu, and Co) concentrations under salinity stress (25 and 150 mM NaCl) in two cultivars (CS-52, and Ashirwad) of *B. juncea.* Both of the cultivars showed an increase in B, Mn, and Cu contents under salt stress, but Fe, Zn, and Co contents were dropped considerably. Salinity stress causes an increase in the accumulation of harmful ions, particularly Na^+, resulting in ion imbalance and hyperosmosis in plants. Nazar et al. [36] found that *B. juncea* plants showed an increased level of Na^+ and Cl^- ion content in the leaves. The physiochemical processes of plant cells are weakened as a result of this imbalance, which hindered plant growth. As a result of excessive Na^+ concentration in cells, K^+ uptake is inhibited, which results in an elevated Na^+/K^+ ratio [53].

El-Badri et al. [54] experimented with five cultivars of *B. napus* (Yangza 11, Zhongshuang 11, Huayouza 62, Fengyou 520, and Yangyou 9) under different salinity levels (50, 100, 150, and 200 mM NaCl). It showed that in the tolerant cultivar Yangyou 9, Na^+ accumulation was lower than the sensitive cultivar Zhongshuang 11, which elevated the K^+ uptake in the tolerant cultivar under stress condition. In Zhongshuang 11, Na^+ content (49 mg g^{-1}) in the seedlings was higher and the K^+ content was lower (5 mg g^{-1}). In comparison to Zhongshuang 11, the Na^+/K^+ ratio in Yangyou 9 shoots reduced by 36% (normal circumstances) and 56% (stress conditions). Goel and Singh [55] stated that under salt stress, genes such as nitrate transporter (NRT), ammonium transporter (AMT), NR, nitrite reductase (NiR), glutamine syntheatase (GA), glutamate dehydrogenase (GDH), and asparagines synthetase (ASN) were decreased in *B. juncea* plants.

2.4 Water relations

The water potential in plant is reduced under saline conditions, subsequently creating water shortage situations in plants [56]. Both in soil solution and in plant organelles, salinity causes an imbalanced solute concentration. Thus, osmotic stress occurs due to loss of plant cell turgidity [57]. Extreme salt stress inhibits the expression of tonoplast aquaporins in plant cells [58] and disrupts metabolic and physiological processes, such as cell meristematic activity and cell elongation. Leaf relative water content (RWC) has long been employed as a measure of a plant's water balance, owing to the fact that it reflects the quantity of water required by the plant to achieve artificial full saturation [59]. It decreases under salinity stress conditions, leading to the loss of cell turgidity in plants. Upon exposure to different levels of salinity stress, different cultivars of oilseed *Brassica* sp. showed a varied reduction in leaf RWC (**Table 2**). An experiment from Mahmud et al. [65] showed that salinity adversely affected the water status of *B. napus* seedlings by reducing their leaf RWC. Under two different (100 and 150 mM NaCl) salinity levels, leaf RWC was reduced by 6% and 11% compared with the unstressed plants.

Another experiment conducted by Fang et al. [33] with *B. napus* plants under different salinity levels (25, 50, and 100 mM of NaCl) showed that 25 mM salt stress had very little effect on root water content at the seedling stage. But under 50 and 100 mM NaCl, water content in their root was decreased than in the control plants.

Species and cultivars	Salinity doses and duration	Response	Reference
B. juncea cv. Pusa Bold	50, and 250 mM NaCl; 10 d	Reduced leaf RWC	[38]
B. juncea cv. Pusa Jai kisan	50 to 200 mM NaCl; 30 d	RWC was increased by 1.4-fold	[60]
B. rapa cvs. Brown Sarson, Yellow Sarson, Toria	50, 100, and 150 mM NaCl; 30 d	Inhibition in RWC by several folds in all three genotypes	[61]
B. juncea cv. Varuna	200 mM NaCl; 90 d	RWC was increased by 40, 36, and 28%, respectively at 30, 60, 90 DAT	[53]
B. carinata cvs. Adet and Merawi	50, 100, and 150 mM NaCl; 35 d	Reduction in RWC by 26%	[41]
B. juncea cvs. CS-52 (tolerant), Ashirwad (sensitive)	25 to 150 mM NaCl; 15 d	Reduced RWC in CS-52 (14%) and Ashirwad (21%), increased water use efficiency in CS-52 (12%) and Ashirwad (55%)	[52]
B. juncea cv. Varuna	120 mM NaCl; 6 d	Declined RWC	[62]
B. juncea cv. Varuna	100 mM NaCl; 7 d	Decrease in RWC by 22%	[63]
B. campestris cvs. BJ-1603, BARI Sarisha-11 and BARI Sarisha-16 (tolerant), BARI Sarisha-14 (sensitive)	8, and 12 dS m^{-1} NaCl;	Significant reduction in RWC in BARI Sarisha-14 under 12 dS m^{-1}	[13]
B. juncea	150 mM NaCl; 7 d	Significant decrease in RWC by 16%	[64]

Table 2.
Changes in water relation parameters of oilseed Brassica sp. under salinity stress.

Also, the osmotic potential of plant leaves alters with the increasing salt concentration in soil. Under 200 mM NaCl stress, *B. napus* showed decreased osmotic potential of −1.82 MPa, whereas it also lowered the RWC of leaves [48]. Similarly, a recent study by Mohamed et al. [43] concluded that 100 mM NaCl solution reduced leaf RWC by 15% and 18% in two cultivars of *B. napus* L., namely Yangyoushuang2 and Xiangyouza553, respectively. Reduction in leaf water potential is also a common salt stress response in plants. According to Wani et al. [42], *B. juncea* showed significantly lower leaf water potential under three different levels of NaCl (78, 117, and 165 mM) concentrations, in a dose-dependent manner.

2.5 Photosynthesis

Salinity hinders the photosynthesis process by limiting plants' stomatal and/or non-stomatal activities to some extent [66]. Salt stress affects stomatal conductance (g_s) initially due to disrupted water relations and then later because of local abscisic acid (ABA) production [67]. Salinization caused some stomatal closure, although photosynthetic losses were predominantly non-stomatal in nature. According to several investigations done with various oilseed *Brassica* cultivars, the duration and doses of salt stress have a substantial impact on plant photosynthetic properties (**Table 3**). Salt stress also has a deleterious effect on photosynthesis because it reduces photosynthetic pigments, and causes considerable changes in photochemistry [5]. The study

Species and cultivars	Salinity doses and duration	Response	Reference
B. juncea cv. Pusa Jai Kisan	100 mM NaCl; 15 d	Reduced net photosynthetic rate (P_n) by 40%, stomatal conductance (g_s) by 26% and intercellular CO_2 concentration (C_i) by 41%	[36]
B. juncea cv. Varuna	100, and 200 mM NaCl; 45 d	Decreased Chl *a* (52%)	[32]
B. napus cv. Zhongshuang 11	100, and 200 mM NaCl; 7 d	Decreased soil and plant analysis development (SPAD) value by 6–20%, P_n by 34–53%, photosystem II (PS II) quantum yield by 27–42%	[68]
B. juncea cv. Pusa Jai Kisan	100 mM NaCl; 30 d	Decreased P_n, g_s, C_i	[69]
B. juncea cv. Varuna	100 and 200 mM; 90 d	Decreased total Chl content by 45%	[40]
B. juncea cv. Varuna	200 mM NaCl; 50 d	Decreased total Chl content, total carotenoids (Car) and g_s	[70]
B. juncea cvs. CS 54, CS 52-1-2012, CS 614–4–1-4-100-13, Pusa bold	12 and 15 dS m^{-1} NaCl; 52 d	Decreased P_n (96%), g_s (86%), C_i (42%) in CS 614–4–1-4-100-13	[71]
B. juncea cvs. Varuna and RH-30	78, 117, and 156 mM NaCl; 60 d	Decreased SPAD Value (31% in Varuna and 37% in RH-30	[42]
B. juncea cv. Pusa Tarak	100 mM NaCl; 15 d	Reduced P_n (43%), C_i, g_s (23%), total Chl content (31%)	[72]
B. campestris cvs. BJ-1603, BARI Sarisha-11 and BARI Sarisha-16, BARI Sarisha-14	8 and 12 dS m^{-1} NaCl; 26–28 d	Decreased P_n, transpiration rate (T_r), g_s and total Chl content	[13]
B. juncea cv. Varuna	120 mM NaCl; 6 d	Decreased Chl *a* and Chl *b* content	[62]
B. juncea	50, and 100 mM; 8 h	Reduced Chl content (42%), PS II efficiency (35%) Increased non-photochemical quenching (npq) by 36%	[14]
B. juncea cv. RGN-48	50 and 100 mM NaCl; 30 d	Decreased SPAD value, P_n (48%), g_s (46%), C_i (41%) in a concentration-dependent manner	[15]
B. juncea cv. Pusa Tarak	100 mM NaCl; 15 d	Decreased Chl concentration, P_n, g_s and C_i	[73]
B. juncea cv. Varuna	100 mM NaCl; 15 d	Reduced stomatal density (19%)	[45]
B. juncea cv. RH0–749	100 mM NaCl; 20 d	Decreased Chl content, P_n, g_s and C_i	[74]

Table 3.
Impact of salinity stress on photosynthesis and associated parameters of oilseed Brassica sp.

performed by Mahmud et al. [65] found that salt stress (100 and 150 mM of NaCl) adversely affected the levels of photosynthetic pigments in *B. napus* plants.

Salt stress has an impact on cell organelles, such as the chloroplast, where most of the photosynthetic activities, such as photosystem I (PS I) and PS II, take place [75]. It reduced the density of active reaction centers and the structural performance of PSII photochemistry, owing to damage on the receptor side of PSII [17]. According to an experiment by El-Badri et al. [54] with five different *B. napus* cultivars, Yangyou 9 and Zhongshuang 11 responded differently under 150 mM NaCl regarding photosynthetic pigments, such as Chl *a,* Chl *b*, and carotenoids (Car). Under salt stress, Chl *a* content was decreased by 36% in Yangyou 9 cultivar and 39% in Zhongshuang 11 cultivar, whereas Chl *b* content was reduced by 39% and 40% in Yangyou 9 and Zhongshuang 11 cultivar, respectively. Also, total Chl was reduced by 38 and 39% in Yangyou 9 and Zhongshuang 11, respectively, under the same dose of salinity. Moreover, Car content in Yangyou 9 and Zhongshuang 11 was decreased by 41% and 35%, respectively, under stress.

2.6 Phenology

Among the other abiotic stresses, salinity has a significant impact on the phenological attributes of the plant family Brassicaceae. Salt stress alters the duration of several physiological stages of plants, from seedling emergence, leaf unfolding, the appearance of first flowering, siliqua formation, grain filling to leaf color changing, and leaf senescence in the end. According to Mohamed et al. [43], 100 mM NaCl showed a significant effect on the duration of the flowering stage of two *B. napus* cultivars (Yangyoushuang2 and Xiangyouza553). Salinity delayed the first appearance date of flowering from 139 d to 143 d and from 141 d to 147 d in Yangyoushuang2 and Xiangyouza553 cultivars, respectively. Moreover, salinity increased the days to 50% flowering in both of the cultivars from 142 d to 146 d and from 144 d to 150 d. Another study by Pandey et al. [76] stated that under 50 mM salt stress, the cotyledonary leaf emergence rate of *B. juncea* was reduced by 30% to the control plants. According to several findings, extreme saline circumstances may bring delayed seed germination [77] because of decreased hydrolytic enzyme activity and seed metabolite mobilization [78]. *B. campestris* seed germination was delayed beyond 24 h under 120 mM salt stress level, as reported by Siddikee et al. [79].

Leaf senescence is another age-dependent phenological characteristic of plants that is related with a wide range of biochemical and molecular changes inside plant organs. Due to the decreased biosynthesis and enhanced breakdown of Chl molecules under salt stress, premature or early leaf senescence occurs in the plant life cycle. Alamri et al. [62] stated that the seedlings of *B. juncea* grown under 120 mM NaCl concentration experienced early leaf senescence.

2.7 Reproductive development

Several additional reproductive stage characteristics, such as flower initiation, anther, and pollen grain development, fertilization, siliqua formation and development, and seed filling, are considerably influenced by the salinity in Brassicaceae plants. During the reproductive stage, *B. napus* seed production potential is indicated by pre-and post-flowering activities. It has been suggested that the reproductive stage is the most sensitive to stress [80]. Flowering and seed filling are the most vulnerable stages of the oilseed Brassicaceae family to extreme salinity stress than the earlier vegetative phases, such as seed germination and seedling growth. Salinity reduces plant fertility by affecting the development of male and female reproductive organs, which are very susceptible to stress [81]. The reproductive stage is intrinsically linked to seed production because fertilization and seed development occur during this stage. Therefore, tolerance to salt stress during this stage is crucial [82].

Arif et al. [83] experimented with BARI Sarisha-8 and BINA sharisha 5 cultivars of *B. napus* under 100 mM NaCl and observed that flowering and siliquae formation were significantly affected by salinity. Discoloration and rolling of the leaves and flowers, inhibition of new buds opening, and the death of young siliquae altogether, leaving the adult siliquae with wrinkled and immature growth. As a result, early maturity symptoms of the seed occurred. However, among two of those cultivars, BARI Sarisha-8 showed more sensitivity at the adult siliquae development stage, whereas the young leaves and siliquae were more vulnerable in BINA sharisha 5. Another experiment by Gyawali et al. [34] with 131 *B. napus* accession lines showed varied responses under different salinity levels (1.4, 5, 10, 15, 20, and 28 dS m^{-1} of NaCl). The number of branches and siliquae were affected more in two of the genotypes (Kuju 29 and Kuju 32). Similarly, in DH12075, there was a failure in fertile branches and siliquae production found under salt stress of more than 10 dS m^{-1}. The number of fertile branches is also affected under salinity. A study from Chakraborty et al. [3] reported that with increasing salinity levels (1.65, 4.50, and 6.76 dS m^{-1} of NaCl), the number of siliquae on primary branches of seven cultivars, for example, CS 52, CS 54, Varuna, Pusa Jagannath, Pusa Agrani and T 9, Sagam of *B. juncea,* and *B. campestris*, were reduced. The reduction was almost 50% under 1.65 dS m^{-1}, whereas, under 6.76 dS m^{-1}, it was one-third of the control plants. Not only the reduction in fertile branch numbers and siliquae but salinity also caused wilting of the reproductive parts (mature flowers and fruits) of *B. napus* [84].

2.8 Oxidative stress

Salt stress leads to ionic toxicity due to higher accumulation of Na^+ and Cl^- ions and depleted potassium ion pool in plants. Disruption in ion homeostasis leads to stomatal closure by hampering the functioning of guard cells, which in turn decreased carbon fixation due to insufficient CO_2 supply in the leaves, and accelerates the generation of the ROS such as H_2O_2, $^1O_2$, $O_2^{\bullet-}$, $HO_2^{\bullet}$, $RO^{\bullet}$, and $^{\bullet}OH$ [7]. Another effect of salinity is to create drought-like conditions in plants due to lower water potentiality and is also responsible for the increase of ROS generation by disrupting photosynthetic activities [56]. Though ROS is beneficial for activating the stress signaling molecules at a certain level, after that it becomes phytotoxic and disrupts metabolic activities and also accountable for the breakdown of different cellular components, namely proteins, lipids, carbohydrates, and nucleic acids [85]. Thus, accelerated activities of ROS boosted protein denaturation, lipid peroxidation, and oxidation of carbohydrates and ultimately created oxidative stress in plants [7; **Figure 1**].

Salt induced oxidative stress due to higher accumulation of ROS observed in *Brassica* sp. However, the extent of salt-induced damage depends on the species, plant growth stage, ion strength, organ specificity, and the components of the salinizing solution [86; **Table 4**]. Sarwat et al. [95] observed that upon exposure to 100 and 200 mM NaCl, *B. juncea* plants resulted in upgraded levels of H_2O_2 content by 1.99- and 3.35-fold, respectively, with a maximum increase of malondialdehyde (MDA) content by 2.19-fold at 200 mM NaCl-treated plants. Salt-sensitive cultivar of *B. carinata* (cv. Adet) showed a higher accumulation of thiobarbituric acid reactive substances (TBARS) compared with the salt-tolerant one (cv. Merawi) in 150 mM NaCl-treated mustard plants [41]. So, it can be stated that degree of salt-induced oxidative damages depends on the cultivar type, dose, and duration of stressed period. Sami et al. [14] found elevated production of H_2O_2 (by 46%) and $O_2^{\bullet-}$ (by 47%) in 100 mM

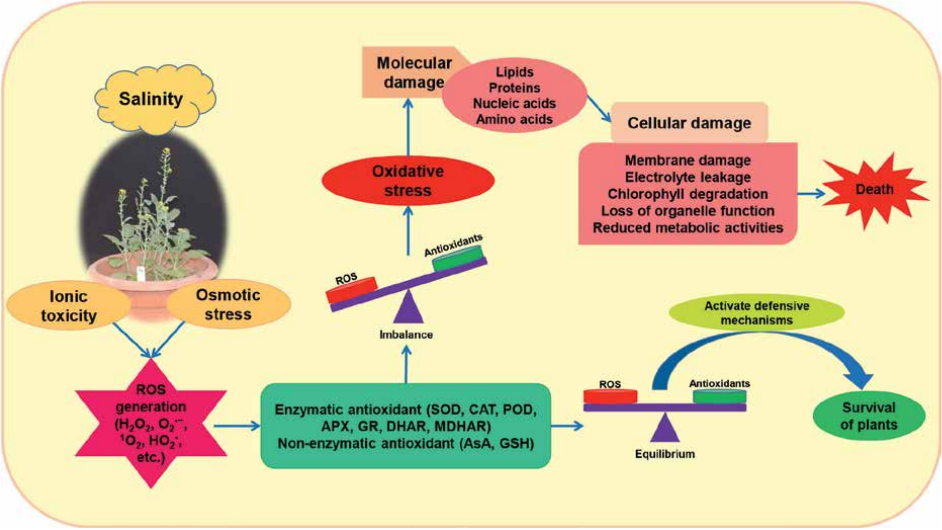

Figure 1.
Schematic representation of ROS-induced oxidative stress in plants and its consequences under salinity.

Species and cultivars	Stress levels	Oxidative damage	References
B. campestris cv. Pusa Gold	40 and 80 mM NaCl; 30 d	Augmented TBARS (129 and 365%) and H_2O_2 (150 and 531%)	[87]
B. juncea cvs. Alankar (Tolerant) and PBM16 (Sensitive)	50 mM NaCl; 15 d	Increased H_2O_2, TBARS, and electrolyte leakage (EL)	[88]
B. juncea cvs. Varuna, RH-30, and Rohini	100 and 200 mM NaCl; 45 d	Enhanced MDA, H_2O_2, and EL	[21]
B. juncea cv. Varuna	150 mM NaCl; 24 h	H_2O_2 and MDA were increased by 2-folds	[89]
B. campestris cv. Shampad	150 mM NaCl; 48 h	Increased H_2O_2 (42%) and MDA (46%)	[90]
B. juncea cv. Varuna	100 mM NaCl; 30 d	Augmented H_2O_2 and TBARS	[91]
B. juncea cvs. Pusa Jai Kisan, Basanti, Rohini, and RH30	100 mM NaCl; 30 d	Elevated TBARS and H_2O_2	[92]
B. juncea cv. Pusa Jai Kisan	100 mM NaCl; 10 d	Increased H_2O_2 and TBARS	[93]
B. juncea cv. Varuna	100 and 200 mM; 45 d	Increased H_2O_2 (60 and 69%) and MDA (20 and 37%)	[32]
B. juncea cv. Pusa Jai Kisan	100 mM NaCl; 30 d	Incremented H_2O_2 and TBARS	[51]
B. juncea cv. Pusa Jai Kisan	100 mM NaCl; 30 d	Upgraded TBARS and H_2O_2	[36]
B. juncea cv. Pusa bold	50 and 250 mM NaCl; 5 d	Increased MDA, EL and H_2O_2	[38]
B. juncea cv. Varuna	100 mM NaCl; 30 d	Enhanced TBARS, H_2O_2, and $O_2^{\bullet-}$	[94]

Species and cultivars	Stress levels	Oxidative damage	References
B. juncea cv. Varuna	100 and 200 mM NaCl; 90 d	Augmented MDA, H_2O_2 and EL	[40]
B. juncea cv. Pusa Jai Kisan	100 mM NaCl; 30 d	Increased H_2O_2 and TBARS	[69]
B. juncea cv. Pusa Tarak	100 mM NaCl; 25 d	Elevation of TBARS (105%) and H_2O_2 (90%)	[72]
B napus cv. BARI Sarisha-13	100 and 150 mM NaCl; 48 h	Augmented H_2O_2 (33 and 50%) and MDA (26 and 60%)	[65]
B. juncea cv. RGN-48	50 and 100 mM NaCl; 30 d	Increased H_2O_2, $O_2^{\bullet-}$ and MDA	[15]

Table 4.
Salt-induced oxidative damages in oilseed Brassica sp.

NaCl-treated *B. juncea* plants together with an augmented level of lipid peroxidation by 55% at a similar level of salinity.

2.9 Yield and quality

Plants exposed to salt stress undergo morphological, physiological, and biochemical changes. It leads to a deleterious influence on reproductive characteristics and ultimate yield reduction in plants [7]. As water is the key element for flowering and siliquae formation in oilseed *Brassica* plants, the accelerated water loss from plant cells induced by salt stress has a significant influence on the reproductive stages. Salinity shows a negative impact on the growth attributes, such as SL, RL, stem diameter, FW, DW, LN, leaf size, LA, and branch number, of oilseed *Brassica* plants. Similarly, it also affects the yield contributing attributes, such as the number of flowers, number of siliquae, seed yield, 1000-seed weight, and oil content of mustard. Moreover, salinity enforces osmotic stress on plants that adversely affect the water conductance status by altering the whole nutritional status of plants [4]. Thus, it causes growth retardation, ionic and nutritional imbalance, disrupted water relations, and photosynthetic inhibition, which subsequently affects the yield attributes in oilseed Brassicaceae family. While experimenting with seven cultivars (CS 52, CS 54, Varuna, Pusa Jagannath, Pusa Agrani, and T 9, Sagam) from *B. juncea* and *B. campestris*, Chakraborty et al. [3] found a significant reduction in seed yield (SY) and oil content in all the seven cultivars. They also reported a great extent of interspecific variation in response to salinity stress in oilseed *Brassica* plants [3, 83].

Likewise, in different studies, a wide range of oilseed *Brassica* cultivars were used to investigate their varied responses in yield attributes under salinity stress (**Table 5**). Reduction in oil content and oil quality is also a common response to salt stress in oilseed *Brassica* plants. Because of the smaller seed size and reduced cellular metabolic activities, total oil content, as well as lipid, protein, and fatty acid content in the oil, is also hampered (**Table 5**). For a balanced osmotic pressure in plant cells, soluble sugar and soluble protein contents play a very significant role. Upon exposure to 100 mM NaCl concentration, two *B. napus* cultivars, Yangyoushuang2 and Xiangyouza553, showed reduced crude oil percentage by 22% and 30%, respectively. Whereas the crude protein percentage was increased by 44% and 24% for both cultivars under the saline condition. Also, seed moisture content, saturated (palmitic and arachidic acids) and unsaturated fatty

Species and cultivars	Salinity doses and duration	Response	Reference
B. napus cv. RBN-3060	100 and 150 mM NaCl; 21 d	Significant reduction in SY, no. of seeds plant^{-1} and 100-seed weight (SW)	[96]
B. juncea cvs. Varuna and RH-30	78, 117, and 156 mM NaCl; 60 d	Decreased no. of pods plant^{-1}, no. of seeds pod^{-1}, 100-SW and SW plant^{-1} in both the cultivars at 156 mM NaCl	[42]
B. juncea cvs. CS 54, CS 614–4–1-4-100-13 (highly salt sensitive) CS 52-SPS-1-2012 (saline tolerant) and Pusa Bold	12 and 15 dS m^{-1} NaCl; 52 d	Decreased SY in CS 614–4–1-4-100-13 and CS 52-SPS-1-2012 by 86% and 60%, respectively.	[71]
B. napus cvs. Yangyoushuang2 and Xiangyouza553	100 mM NaCl; until final harvest	Reduced total no. of effective siliquae (TES), biomass of effective siliquae (ESB), no. of green siliquae, SY and 1000-SW	[43]
B. napus cv. Okapi	50, and 100 mM NaCl; at flowering stage	Reduced oil content by 11% and SW by 35% under 100 mM NaCl	[97]

Table 5.
Changes in yield and quality traits of oilseed Brassica sp. upon salinity stress.

acid concentrations, glucosinolate in both cultivars were greatly influenced under salt stress. But the oleic acid concentration in Xiangyouza553 cultivar remained unchanged under stress [43]. Six ecotypes of *B. napus* were tested under 50, 100, and 150 mM NaCl stress, which showed a similar response in yield attributing characters. The ecotypes were Super, Sandal, Faisal, CON-111, AC Excel, and Punjab, among which the number of pods per plant was reduced significantly under 150 mM NaCl in Punjab cultivar. Also, a similar trend in reduction was observed for 1000-seed weight in the same cultivar with increasing salt concentration, while the other varieties showed little to no response regarding those attributes [98].

3. Mechanisms of salt tolerance in oilseed *Brassica*

To overcome salinity-induced osmotic and ionic stress, plants evolve avoidance or tolerance mechanisms in order to protect the cellular components from sustaining the growth and development. Ion homeostasis, vacuolar compartmentalization, accumulation of secondary metabolites, hormonal regulation, osmolytes production, and by activating defensive responses, plants endure the salinity-induced damages and enhance the stress tolerance.

3.1 Screening of salt-tolerant traits

Screening of salt-tolerant cultivars of *Brassica* sp. is one of the most effective approaches to minimize the loss of yield; therefore, it has been attracted by many researchers and plant breeders. While working with 25 Indian *B. juncea* genotypes, Sharma et al. [99] reported that the lowest reduction of germination and speed of germination was found in the RB-10 and PR-2004-2 genotypes. Besides, the highest salt tolerance index for root growth was observed in six genotypes of mustard, such as RB-10, SKM-450, RK-05-02, JGM-03-02.RL-2047, and NRCD-509, and salt tolerance index for the dry matter was also highest in the RB-10 and PR-2004-2 genotypes. Finally, based on the results of germination, growth, and salt tolerance index, Sharma et al. [99] proposed that among the 25 genotypes, highly tolerant genotypes were RB-10 and PR-2004-2, whereas GN-48, JKMS-2, SKM −450, and CS-610-5-25P were categorized as tolerant and NDR-05-01, PBR 300, RK-05-01, NPJ-93, PDR-1188, and RGN-145 were moderately tolerant to salinity. Similarly, Yousuf et al. [39] experimented with 25 genotypes of *B. juncea* and reported among the 25 genotypes highest lipid peroxidation and lowest soluble protein content, antioxidant activities, and biomass accumulation were found in the Pusa Agrani genotype in a dose-dependent manner of salinity. Whereas, in CS-54 genotype salinity least affected the biomass accumulation, antioxidant activities together with minimal oxidative damages suggesting that CS-54 was more tolerant and the Pusa Agrani was sensitive genotype [39]. While working on the 21 genotypes of *B. juncea*, Prasad et al. [100] found the highest GP and vigor index in CS2009–347, followed by CS-52 genotype, and identified CS2009–347 and CS-52 as the most tolerant genotypes, whereas CS2009–256 and CS2009–145 genotypes were the susceptible genotypes under salinity. Previously, based on the P_n, g_s, T_r, water use efficiency, C_i and other physiological characters of 10 genotypes of *B. juncea*, Chapka Rohini was found to be the most susceptible to salinity, while Varuna was the most resistant genotype [101]. Moreover, Hossain et al. [13] studied the performance of four genotypes of *B. campestris* under salinity and found lower MDA, higher Pro, and antioxidants' activities in the salt tolerant genotypes (BJ-1603, BARI Sarisha-11 and BARI Sarisha-16) in comparison with the salt-sensitive genotype (BARI Sarisha-14).

3.2 Osmoregulation

To negate the cellular dehydration, plants must retort the osmotic balance, so it activates its osmoregulation mechanism to enhance salt tolerance [102]. In order to accomplish this, plants synthesize different compatible solutes or osmoprotectants such as Pro, glycine betaine (GB), sugars, trehalose, polyamines, organic acids, and amino acids to maintain the osmotic balance under salt stress. Besides osmotic balance, osmolytes are also engaged in ROS-scavenging, protect photosynthetic apparatus, maintain membrane integrity and protein stabilization [103]. In salt-tolerant cultivars of mustard, higher accumulation Pro was observed compared with the salt-sensitive cultivar [13]. Similarly, Ghassemi-Golezani et al. [104] found that accumulation of Pro and soluble sugars increased in a dose-dependent manner. So, based on the available literature, it can be stated that the accumulation of osmolytes helps to maintain osmotic adjustment and also induce tolerance in the salt-stressed *Brassica* plants (**Table 6**).

3.3 Hormonal regulation

Hormones actively take part in the mediation and modulation of plant's responses to varying environmental conditions. The regulations of plant hormones are prominent in salt-stressed condition, and it can induce plant-adaptive mechanisms to cope with the stressed condition [106; **Table 7**]. Abscisic acid is a well-known stress-responsive plant hormone that helps in the mitigation of salt stress through increasing concentration within the plant to control stomatal closure and ultimately initiates

Species and cultivars	Stress exposure	Osmolytes accumulation	References
B. juncea cvs. Varuna, RH-30, and Rohini	100 and 200 mM NaCl; 45 d	Proline (Pro) was increased in a dose-dependent manner	[21]
B. juncea cv. Varuna	150 mM NaCl; 24 h	Increased Pro and GB by 2- and 3-folds	[89]
B. juncea cvs. Alankar and Chutki	100 mM NaCl; 30 d	Higher accumulation of Pro in Alankar than Chutki	[105]
B. juncea cvs. Pusa Jai Kisan, Basanti, Rohini, and RH30	100 mM NaCl; 30 d	The highest Pro was in Pusa Jai Kisan and lowest was in RH30	[92]
B. juncea cv. Varuna	100 and 200 mM; 45 d	Pro was enhanced by 42 and 59%	[32]
B. juncea cv. Pusa Jai Kisan	100 mM NaCl; 30 d	Increased Pro content	[51]
B. juncea cv. Varuna	100 and 200 mM NaCl; 90 d	Pro was increased by 58%	[40]
B. carinata cvs. Adet and Merawi	50, 100 and 150 mM NaCl; 28 d	Lower accumulation of Pro in Merawi then Adet	[41]
B. napus cv. BARI Sarisha-13	100 and 150 mM NaCl; 48 h	Augmented Pro accumulation by 109 and 184%	[65]
B. juncea cv. Pusa Tarak	100 mM NaCl; 25 d	Pro was enhanced by 60%	[72]

Table 6.
Accumulation of osmolytes of oilseed Brassica sp. under salt stress.

defense mechanisms. Upon exogenous application, ABA enhanced salt tolerance through attenuating the ionic and oxidative stress caused by salinity by lowering the accumulation of Na^+ and Cl^-, and reducing the overproduction of H_2O_2 and TBRAS contents in *B. juncea* [74]. Additionally, the antioxidant activities of *B. juncea* were recorded to be increased even under salt stress due to ABA application as a consequence of increased activities of APX, GR, and SOD. Similarly, auxin, particularly indole acetic acid (IAA), plays an important role in the regulation of salt stress in *Brassica*. Being growth-generating hormone, auxin has the capacity to stimulate the growth attributes of plants, and this phenomenon also took place under salt stress in *Brassica* crops. Besides improving growth and photosynthetic characteristics including the recovery of stomatal aperture, the link between auxin and ROS resulted in well adaptation of *B. juncea* against salt stress [107] through uplifting enzymatic (CAT, POD, and SOD) and non-enzymatic (Pro) antioxidant activities.

Exogenous application of jasmonic acid (JA) increased ROS scavenging CAT, SOD, and POD activities with reduced TBARS content and thus, indicated amplification of salt tolerance of *B. napus* [110]. As a signaling molecule, ethylene (ETH) can modulate plant stress tolerance to some extent. Rasheed et al. [114] experimented that ethephon (an ETH-releasing compound) applied *B. juncea* plant resulted in better photosynthetic activities with improved stomatal behavior under salt-induced condition. With an increased APX, GR, and GSH activities and decreased H_2O_2 content within the plant, ethephon further strengthens the tolerance mechanism of *B. juncea* under the stressed condition imposed by salt. A similar role of ethephon was observed by Fatma et al. [45], whereas the elevated activity of AsA-GSH cycle to reduce the toxicity of H_2O_2 content in guard cells together with restricted ABA to initiate stomatal closure proved the salt tolerance mechanism of ethephon in *B. juncea.* Salicylic acid

Species and cultivars	Hormones	NaCl levels	Protective effects	References
Brassica juncea cv. RH0–749	Abscisic acid (ABA)	100 mM; 20 d	Reduced Na^+, Cl^-, H_2O_2 and TBARS contents. Increased photosynthetic parameters, Rubisco activity and antioxidant enzymatic activities.	[74]
B. juncea cv. Varuna	Auxin	100 mM; 38 d	Increased root and shoot length and dry mass. Improved leaf characteristics. Enhanced SOD, POD, CAT activities and Pro content.	[107]
B. napus cv. Talaye	Jasmonic acid (JA)	330 mM; 28 d	Ameliorated relative growth rate, net assimilation rate and RWC. Increased photosynthesis with reduced respiration rate. Decreased MDA content and LOX activity.	[108]
B. nigra	JA	80 mM; 21 d	Increased g_s and quantum yield of PS II. Lower transpiration rate with higher SPAD value.	[109]
B. juncea cv. Pusa Jai Kisan	Ethylene (ETH)	100 mM; 30 d	Downregulated ionic toxicity. Upregulated SOD, APX and GR activities and redox state. Increased P_n and Rubisco activity.	[69]
B. juncea cv. Varuna	ETH	100 mM; 30 d	Diminished Na^+ and Cl^- contents in roots and leaves. Reduced H_2O_2 and TBARS contents and increased GSH/GSSG ratio. Improved P_n and anthocyanin content.	[45]
B. napus cv. Okapi	Salicylic acid (SA)	100 mM; 45 d	Reduced Na^+ and increased K^+ level. Improved plant nutrients, Chl contents and plant biomass. Increased CAT, SOD and POD activities.	[110]
B. carinata cv. Adet and Merawi	SA	150 mM; 28 d	Increased plant height, LN and LA. Improved plant biomass, Chl and Car contents. Revived leaves functional attributes, antioxidant enzyme activities and reduced leaf TBARS content.	[41]
B. juncea cv. Varuna	Brassinosteroids (BRs)	100 mM; 38 d	Recovered plant growth in height and weight. Improved guard cells, leaf area index and Chl contents. Increased K^+/Na^+ ratio with decreased EL and MDA content. Escalated level of N and declined ABA content.	[111]
B. juncea cv. NO BJ16–9	BRs	150 mM; 36 h	Reduced cell damage, electrical conductivity (%) and MDA content. Ameliorated CAT, SOD and APX activities.	[112]

Species and cultivars	**Hormones**	**NaCl levels**	**Protective effects**	**References**
B. nigra cv. Black mustard	BRs	12 dS m^{-1}; at sowing time	Decreased root shoot Na^+ content with increased Ca^+ and K^+/Na^+ ratio. Increased Chl, Car and anthocyanin contents. Improved CAT, SOD and POD activities.	[104]
B. napus cv. Vestar	BRs	150 mM; 6 d	Reduced Na^+, Cl^- and TBARS contents. Improved water content (%) and plant nutrients.	[113]
B. napus cv. Yangyoushuang2 and Xiangyouza553	Melatonin (MEL)	100 mM; 131 d	Improved K^+/Na^+ and Ca^{2+}/Na^+ ratio. Increased Chl *a*, *b*, Car contents and g_s. Enhanced yield attributes and fatty acid composition.	[43]
B. juncea cv. Green mustard	MEL	150 mM; 38 d	Attenuated plant height, leaf growth and Chl concentration. Improved photosynthesis, leaf RWC and antioxidant activities.	[64]

Table 7.
Hormonal regulation in salt stress tolerance of oilseed Brassica sp.

(SA) is widely used in enhancement of crop stress tolerance and effective against salt stress too. Besides improving the physiological attributes of *B. carinata*, such as g_s, P_n, T_r, and water use efficiency, SA can modulate TBARS and H_2O_2 contents to maintain the membrane stability under salt exposure [41]. Moreover, SA-treated *Brassica* plant can withstand salt-induced conditions due to the antioxidative mechanism of this hormone consisting of increased enzymatic (SOD, CAT, and POD) activities and ascorbate-glutathione pathway and that can ultimately maintain cell redox potential and ameliorate oxidative stress damage conferring salt tolerance ability of SA [41].

Brassinosteroids (BRs) can activate the stress-regulated genes and so take part in the stress amelioration of crops. In *B. juncea*, BRs in the form of 24-Epibrassinolide (24-EBL) showed better performance in bringing down the concentration of Na^+, compliment with more K^+ and therefore, give rise to an increased plant height with higher fresh and dry biomass and improved Chl contents against salt stress [111]. The abatement of salt toxicity was further proved in that experiment by reduced endogenous ABA accumulation, EL, and lipid peroxidation together with uplifted GK and PROX activities that increase the Pro biosynthesis to combat the stressful condition in *B. juncea*. Retarded growth and quality of *B. nigra* were attenuated upon 24-EBL application with better antioxidant activities as 24-EBL activated antioxidant enzymes (SOD, POD), controlled MDA content, and encouraged the generation of secondary metabolites (phenolic and flavonoid contents) as well as anthocyanin content [104]. Moreover, the resistance potentiality of *B. juncea* after applying BRs has been reported as a consequence of adjusted ROS contents, uplifted antioxidant enzyme activities, and increased transcript gene (*BjAOX1a*) that cause elevation of a cyanide-resistant respiratory activity, to enhance the tolerance mechanism of *Brassica* in salt-induced condition [112]. Recovery of salt-induced stress by melatonin (MEL) has been proved in many kinds of research and so in oilseed *Brassica*. Like other beneficial hormones, MEL is effective in amelioration of salt stress in *B. napus* growth, and in addition, MEL encourages the gene expression that linked with campesterol, JA, and GA hormones synthesis and properly regulates these hormones thus, ensured the salt tolerance mechanism of MEL [115]. Apart from this, root growth, which is the prime challenge under salt stress, was recorded to be uplifted after MEL treatment, resulted in increased root length, thickness, viability, and lateral root formation in *B. napus* due to the ability of MEL to impair the oxidative stress and maintain ion homeostasis [116].

3.4 Antioxidant defense

To protect the cellular organelles from ROS-induced damages, plants are furnished with defensive mechanisms containing non-enzymatic and enzymatic antioxidants. In plants, non-enzymatic antioxidants such as AsA, GSH, flavonoids, and tocopherols, and enzymatic antioxidants such as SOD, APX, DHAR, MDHAR, GR, GST, glutathione peroxidase (GPX), and POD work in a coordinated manner in order to detoxify ROS [7]. In plant cells, SOD first activates, which converts $O_2^{\bullet-}$ into H_2O_2, further transformation into less-reactive molecules take place in the presence of CAT, POD, GPX, or in the AsA-GSG cycle [117]. Under stressed conditions, the AsA-GSH cycle plays a crucial role in neutralizing H_2O_2 where AsA and GSH are accompanied by APX, DHAR, MDHAR, and GR in a cyclic manner [118]. Besides this, CAT, GST, GPX, polyphenols, and thioredoxins are also engaged in scavenging electrophilic substances, xenobiotics, and herbicides, and finally help in vacuolar transportation [119]. Plants are naturally equipped with the defensive mechanism to survive the stressed period by augmenting their activities. A number of papers have been published on the activities of antioxidant enzymes of *Brassica* sp. in salt-stressed conditions (**Table 8**). Upon exposure to salt stress (50 and 100 mM NaCl) to *B. juncea* cv. RGN-48, the activities of CAT, SOD, and POD are enhanced compared with the unstressed plants [15]. While working with four genotypes of *B. napus* (viz., BJ-1603, BARI Sarisha-11, BARI Sarisha-14, BARI Sarisha-16), Hossain et al. [13] found that activities of SOD, CAT, POD, and GPX were unchanged, whereas MDHAR and DHAR activities were decreased in the salt-sensitive cultivar (BARI Sarisha-14). On the contrary, antioxidant enzyme activities were increased in the salt-tolerant genotypes (BJ-1603, BARI Sarisha-11, BARI Sarisha-16) of mustard [13]. Another study from Husen et al. [41] found elevated activities of SOD, CAT, and POD in both cultivars (Adet and Merawi) of *B. carinata* upon exposure to salt stress, but in cv. Adet, the CAT and POD activities were higher, while activity SOD was more in cv. Merawi.

3.5 Stress signaling

A complex array of mechanisms between different intracellular components is involved in stress signaling comprising reception, transduction, and induction of stimuli (**Figure 2**). ROS was previously believed as toxic molecule, but nowadays, ROS plays the role of signaling cascades. ROS can activate mitogen-activated protein kinase (MAPKs) pathway, which regulates the ionic homeostasis and osmotic adjustments [118]. In a well-organized and sequential pathway, MAPK cascades activated where phosphorylation of MAPK kinase kinase (MAPKKK) took place and transformed into MAPK kinases (MAPKKs) and MAPKs. Thus, the MAPK cascades transfer the stimuli of any environmental stresses to the target proteins and finally enhance gene expression and stress adaptation [120]. Thus, to maintain the osmotic adjustment, MAPK receives and transduces specific signals for the activation of genes

Species and cultivars	**Stress exposure**	**Antioxidants name**	**Activity**	**Reference**
B. campestris cv. Pusa Gold	40 and 80 mM NaCl; 30 d	SOD, APX, GR	Increase	[87]
		AsA, GSH	Decrease	
B. juncea cvs. Alankar (tolerant) and PBM16 (sensitive)	50 mM NaCl; 15 d	GSH, APX, GR, SOD	Increase	[88]
B. juncea cvs. Varuna, RH-30, and Rohini	100 and 200 mM NaCl; 45 d	SOD, CAT, APX, GR	Increase	[21]
B. juncea cv. Varuna	150 mM NaCl; 24 h	SOD, CAT, GR, APX	Increase	[89]
		POD	No change	
B. campestris cv. Shampad	150 mM NaCl; 48 h	GSH, GSSG, APX, GST, GR	Increase	[90]
		CAT	Decrease	
		AsA, MDHAR, DHAR, GPX	No change	
B. juncea cv. Pusa Jai Kisan	100 mM NaCl; 10 d	GSH	Increase	[93]
B. juncea cv. Varuna	100 and 200 mM; 45 d	GSH, GSSG, SOD, POD, APX, GR, GST, GPX	Increase	[32]
		AsA, MDHAR, DHAR, CAT	Decrease	
B. juncea cv. Pusa Jai Kisan	100 mM NaCl; 30 d	GSH, GSSG, DHA, APX, DHAR, GR	Increase	[36]
		AsA	Decrease	
B. juncea cv. Varuna	100 mM NaCl; 30 d	GSH, APX, CAT	Increase	[94]
B. juncea cv. Varuna	100 and 200 mM NaCl; 90 d	GSH, GST, GR, APX, SOD	Increase	[40]
		AsA, CAT	Decrease	
B. juncea cv. Pusa Jai Kisan	100 mM NaCl; 30 d	GSH, SOD, APX, GR	Increase	[69]
B. napus cv. BARI Sarisha-13	100 and 150 mM NaCl; 48 h	DHA, GSH, GSSG, APX, GR, SOD, GPX	Increase	[65]
		AsA, DHAR, MDHAR, CAT	Decrease	
B. juncea cv. Pusa Tarak	100 mM NaCl; 25 d	SOD, CAT, APX, GR	Increase	[72]

Table 8.
Hormonal regulation in salt stress tolerance of oilseed Brassica sp.

to synthesize osmoprotectants, such as Pro, trehalose, and sugars, which are involved in ROS quenching, maintains membrane integrity, and stabilizes proteins by sustaining water transportation system [121].

Excessive Na^+ elevates intracellular Ca^{2+} in the cytosol and activates Ca^{2+} signaling cascades. Calcium-permeable channel OSCA1 found in the plasma membrane as a putative osmosensor under osmotic stress due to the loss of function mutant *osca1* thus enhanced Ca^{2+} signaling pathway. Besides this, antiporter KEA1/2 and KEA3 also

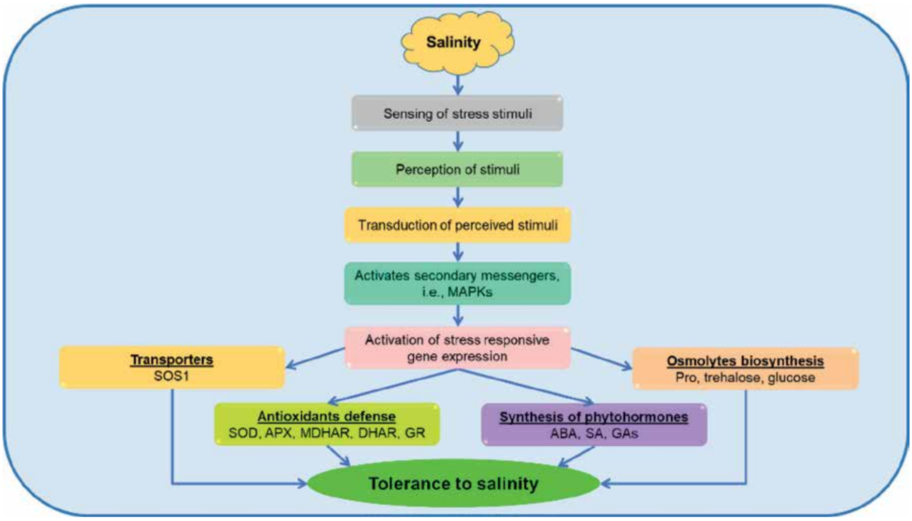

Figure 2.
A schematic representation of mechanisms of stress signaling of plants under salinity. After sensing the stress stimuli, plants activate secondary messengers of mitogen activated protein kinase (MAPKs) pathway through perception and transduction, which regulates adaptive responses. Specific gene expression plays vital role in synthesizing osmolytes (proline, pro; trehalose; glucose), phytohormones (abscisic acid, ABA; salicylic acid, SA; gibberellins, GAs), regulates defensive responses of antioxidants (superoxide dismutase, SOD; ascorbate peroxidase, APX; monodehydroascorbate reductase, MDHAR; dehydroascorbate reductase, DHAR; glutathione reductase, GR), and transporters of salt overly sensitive (SOS) in inducing tolerance of plants against salinity.

augmented the osmotic-stress-induced Ca^{2+} signaling cascades by exchanging K^+ in the plastids [122, 123]. Furthermore, ionic-stress-induced Ca^{2+} signaling mediated Na^+-occupied calcium-permeable channel where the mutant of monocation-induced Ca^{2+} increases 1, *moca1* hypersensitive to salinity and enhanced Ca^{2+} influx by controlling the Na^+ transportation [124]. The plasma membrane receptor-like kinase FERONIA (FER), leucine-rich-repeat receptor kinase, and hydrogen-peroxide-induced Ca^{2+} increases 1 (HPCA1) also involved in the stabilization of plasma membrane by transmitting the stress stimuli, thus maintain cell wall integrity and stomatal closure under salinity [125, 126].

Along with the Ca^{2+} signaling cascades, the salt overly sensitive (SOS) pathway also plays a crucial role in alleviating the ionic toxicity through exporting Na^+ from cytoplasm to apoplast. Under salt stress, Ca^{2+} sensors (SOS3/SCaBP8) received the signals and transferred them to the serine/threonine protein kinase (SOS2) where it is phosphorylated with the SOS1 and increased salt tolerance of plants through augmenting the Na^+/H^+ exchange capacity [127, 128]. Besides, ROS signaling activates defensive responses, which enhances antioxidant activities and scavenges ROS, thus helps in protecting the intracellular molecules through maintaining redox homeostasis [129].

Under salinity, osmoregulation is properly maintained as a result of ROS-induced activation of MAPK, and the Ca^{2+} signaling regulates the closing and opening of stomata. Besides this, H_2O_2 also played a crucial role in signaling cascades. Being a part of oxidative metabolism, H_2O_2 interplayed in between other biomolecules, such as ABA, ETH, SA, and NO at nontoxic level [130]. Thus, it helps to regulate the stressed period and enhance the tolerance capacity of the plants. Likewise, hydrogen sulfide (H_2S) is a small gaseous signaling molecule performed in traversing of the intra- and inter-cellular domains and regulates the redox homeostasis in plants under stress. Moreover, H_2S inhibits the dynamic synchronization of antioxidant enzymes and NADPH oxidase activity and induces the tolerance against stress [131]. Another molecule is nitric oxide (NO), which has capacity to modulate reactive nitrogen species (RNS), alter protein activity, metal nitrosylation, GSH biosynthesis, formation of tyrosine nitration/peroxynitrite, *S*-glutathionylation and *S*-nitrosylation to augment the stress endurance of plants [132]. Biosynthesis of PAs is regulated with the enhanced activity of NO, where NO reduces the PA oxidase activity, thus inhibiting the breakdown of PA and helping to resist the salt stress [133]. Furthermore, CO also increased salt tolerance through the NO-mediated signaling pathway, where plasma-membrane-localized proton pump (H^+-ATPase) and antioxidant activities enhanced the stress tolerance capacity of plants [134]. Phytohormones have an indispensable role in regulating and enhancing stress tolerance of plants. Under salt stress, ABA activates kinase cascade pathway and regulates gene expression, thus increases endogenous ABA levels, which leads to stomatal closure to maintain the water balance in plants and also enhance selective absorption of ions for transferring Na^+ from the cytoplasm to the vacuole [135]. Whereas, GAs works antagonistically with the ABA to regulate the germination of seeds by augmenting enzymes and H^+-ATPase activity. Beside this, GAs also reduce g_s and increase transpiration and water use efficiency of plants to sustain the salt stress [136]. Cytokinins (CKs) perform differential role in the plant growth and development includes cell division, chloroplast biogenesis, apical dominance, leaf senescence, vascular differentiation, nutrient mobilization, anthocyanin production, and also known to induce salt tolerance in plants [137]. Synthesis of BRs under salinity enhanced the stress tolerances by regulating ionic homeostasis and osmoregulation and also responsible for the translational change of the stress-responsive proteins through expressing the stress-responsive genes to regulate Na^+/H^+ antiporters activity [138]. Further growth of plants is modulated by the enhanced activity of auxin, whereas ETH signaling, together with ROS, is liable for the AsA biosynthesis under salt stress [139]. There are many biomolecules involved in the stress signaling pathway to adapt to adversity. But the interaction of these biomolecules and cross talk among the components are complex and yet to be discovered to interpret the adaptation of plants under salinity.

3.6 Microbes-assisted salt tolerance

Microorganisms such as bacteria, mycorrhiza, and fungi are mostly used agents in mitigation of salt stress of *Brassica* inhabited in either the host plant or rhizosphere through promoting the growth of particular hosts [140; **Table 9**]. For instance, plant-growth-promoting bacteria *Pseudomonas fluorescens* inoculation in *B. napus* proved to be an effective approach in mitigation of salt stress in *Brassica* crops, as the inoculated seedling under salt stress gave higher plant biomass, RWC, and Pro content for better osmoregulation during stressful conditions [142]. In saline soil, recovery of damaged *B. napus* was recorded by Latef et al. [146] as a consequence of *Azotobacter chroococcum* inoculation, whereas microbes not only improved plant morphological and physiological characteristics but also reduced Pro, MDA, and H_2O_2 contents to protect salt-induced cell damage. Additionally, the activities of antioxidant enzymes, namely SOD, POD, APX, were also augmented after inoculation conferring salt tolerance while reducing Na^+ level within the plants [146]. *Rhizobium* strains capable to produce ACC-deaminase improved nutrients (N, P and K) uptake of *B. napus* in salt-induced condition and thereby, growth parameters, such as plant height, DW, stem diameter, LN, and RWC, were also increased conforming salt tolerance to *B. napus* [143].

Species and cultivars	Salinity levels	Microbial Inoculation	Tolerance traits	References
Brassica napus cv. Westar canola	250 mM NaCl; 4 d	*Pseudomonas putida*	Uplifted shoot FW and DW and more Chl content. Declined ETH level, H_2O_2 content and Na^+ concentration.	[141]
B. juncea cv. Varuna	200 mM NaCl; 45 d	*Trichoderma harzianum*	Increased plant height, DW, Chl and oil contents. Reduced Na^+, H_2O_2 and MDA contents. Enhanced activities of SOD, POD, DHAR, MDHAR, APX, GR, AsA and GSH/GSSG ratio.	[32]
B. napus cv. Hyola308	150 mM NaCl; 21 d	*P. fluorescens*	Upregulation of plant FW and DW with increased relative water and proline contents. Improved protein activity responsible for glycolysis, tricarboxylic acid cycle and metabolism of amino acid.	[142]
B. napus cv. Suyou No. 1	100 mM NaCl; 15 d	*Enterobacter cloacae*	Raised SL, RL, secondary roots number and Chl content. Higher IAA content with lower ETH emission. Increased SOD, POD and CAT activities with decreased MDA content.	[31]
B. napus cv. RGS003	50 mM NaCl and $MgCl_2$; 121 d	*Rhizobium legominozaroum*	Elevated plant height, DW, stem diameter, LN and RWC. More nutrient (N, P and K) uptake.	[143]
B. napus	300 mM NaCl; 42 d	*P. sutzeri*	Increased plant height, biomass, LN and Chl content. Reduced lipid peroxidation and GSH content. Enhanced cell number with more thickness.	[144]
B. juncea cv. Variety 749	12 dS m^{-1} NaCl; 33 d	*Pseudomonas azotoformans*	Improved germination and seedling growth. Increased root and shoot DW. Uplifted IAA and aminolevulinic acid production with more P and K solubilization.	[44]
B. napus cv. Jura	200 mM NaCl; 112 d	*T. parareesei*	Increased crop productivity and gene expression for ETH pathway.	[145]
B. napus cv. Pactol	11.5 mmhos cm^{-1} EC; 66 d	*Azotobacter chroococcum*	Uplifted growth attributes, photosynthetic pigments, soluble sugar and protein contents. Alleviated antioxidant enzymatic activities and nutrient contents.	[146]
B. napus cv. SY Saveo	160 mM NaCl; 7 d	*Arthrobacter globiformis*	Improved seed germination (%), SL and RL. Increased water content (%), Chl and CAR contents. Elevated SOD activity and Pro content with reduced membrane injury index.	[147]

Table 9.
Microbes-assisted tolerance in Brassica under salt stress.

Inoculation of growth-promoting rhizobacterial strains *Pseudomonas* in regulation of salt mitigation activities of *B. juncea* has been confirmed by recording their positive role in increased GP, growth factors, ACC-deaminase activity, and aminolevulinic acid production even under high salt concentration [44]. Additionally, this microbe also takes part in auxin production, ETH reduction through ACC activity, and nutrient solubilization and so provides better establishment of *B. juncea* against extreme salt exposure [44].

The impaired growth of salt-induced *B. napus* can be ameliorated by applying mycorrhizae (*Glomus macrocarpium*), as inoculation of these microbes increases K^+/Na^+ in plant compared with salt-stressed plant alone, and so further abatement of salt damage was recorded in increased growth and yield parameters of *B. napus* with improved nutrient contents as well [148]. The amino acid and fatty acid profile also showed better performance in mycorrhizal inoculated plant under salt exposure in comparison with uninoculated stressed *B. napus* [148]. Moreover, proteins that are involved in cell function, leaf photosynthesis, redox potential, and amino acid metabolism are more prevalent in bacteria applied salt-stressed *B. napus* compared with salt-stressed seedling alone, and this is an important indication of salt tolerance mechanism induced by bacteria [142]. *B. napus* seed inoculation with *Arthrobacter globiformis* benefits higher GP with better seedling growth in high level of salt exposure, and this plant-microbe interaction also facilitates in higher phenolic compounds together with phenylalanine ammonia-lyase and SOD activities and more Pro accumulation as well to counteract salt-stressed damage in salt sensitive plants also [147].

4. Agronomic managements for salt tolerance in oilseed *Brassica*

Brassica adopts many intrinsic mechanisms to tolerate the salt stress through activating stress tolerance traits, and further enhancement of salt endurance capacity could be achieved by incorporating agronomic managements. These management practices include nutrient management, seed priming, application of hormones and other inorganic and organic elicitors. Some of them are presented in the **Table 10**.

Nutrient management in the salt-affected field could be an effective way to counteract the adversity of salinity in *Brassica*. Application of N, Zn, and Ca in salt-stressed *Brassica* plants significantly improved the stress tolerance [40, 51]. For instance, application of N (5, 10, and 20 mM) reduced the leaf Na^+ and Cl^- contents, oxidative stress markers (H_2O_2 and TBARS) and helped to regulate osmotic balance in *B. juncea* under salinity [51]. Foliar spraying of 1 mM Zn improved growth and biomass of *B. juncea* in NaCl stress (100 and 200 mM) through reducing oxidative stress by augmenting antioxidants activities [40]. Sarkar and Kalita [153] applied selenium nanoparticles (SeNPs) in salt-stressed *B. campestris* plants and found that SeNPs (12.5 and 50 mg L^{-1}) improved GP, SL, RL, and Chl content and thus enhanced salt tolerance of the plants.

Seed invigoration through priming could be an effective tool to enhance germination of *Brassica* under salinity. Comparative study by using three different priming techniques, such as hydro-priming, chemo-priming ($CaCl_2$), and hormonal priming (ABA) in salt-stressed *B. juncea*, Srivastava et al. [154] reported that GP and the rate of germination were increased in the primed seeds than the non-primed. Seed priming with different concentrations of SA (1, 1.5, 2, and 5 mM) improved the GP and the average velocity of germination of *B. napus* under salt stress [84].

Species and cultivars	Stress exposure	Elicitors and dose	Application method	Effects	References
B. juncea cv. Varuna	150 mM NaCl; 24 h	0.2 mM sodium nitroprusside (SNP)	Added with nutrient solution	Increased total Chl, leaf RWC, carbonic anhydrase (CA) and NR activity. Reduced Na^+ and enhanced K^+ and Ca^{2+}.	[89]
B. napus cv. ZS 758	100 and 200 mM NaCl; 14 d	5-Aminolevulinic acid (ALA); 30 mg L^{-1}	Foliar spray	Enhanced SL, FW and DW. Increased Chl *a*, Chl *b*, Car, and photosynthetic efficiency (F_v/F_m). Decreased leaf and root Na^+ and K^+.	[149]
B. juncea cvs. Alankar and Chutki	100 mM NaCl; 30 d	N and/or S; 100 mg kg^{-1} soil	Mixed with soil	Increased F_v/F_m and Chl. Increased LA and DW. Enhanced N content and NR activity.	[105]
B. napus cv. Westar bred	175 mM NaCl; 14 d	24-epibrassinolide (24-EBL); 10^{-10} M	Added with nutrient solution	Increased SL, LA, FW and DW. Increased RWC and reduced Pro. Decreased MDA, phenolics and flavonoids.	[150]
B. juncea cv. Varuna	100 mM NaCl; 30 d	NO; 50, 100, and 150 μM SNP	Foliar spray	Decreased leaf Na^+ and Cl^-. Increased Chl, F_v/F_m, Rubisco activity, P_n, LA and DW at 50 and 100 mM SNP.	[91]
B. juncea cv. Varuna	100 mM NaCl; 15 d	S; 100 and 200 mg kg^{-1} soil	Mixed with soil	Reduced leaf Na^+ and Cl^-. Increased ATP-sulfurylase activity and cysteine content. Enhanced Rubisco and P_n activity.	[151]
B. juncea cv. Pusa Jai Kisan	100 mM NaCl; 30 d	SA; 0.5 mM	Foliar spray	Declined leaf Na^+ and Cl^-. Upgraded ATP-sulfurylase serine acetyl and transferase activity Increased P_n, g_s, C_i, LA and DW.	[36]
B. napus cv. Sary	150 mM NaCl; 7 d	Lipoic acid; 0.1 mM	Foliar spray	Increased FW and DW of shoot and root. Reduced MDA and Pro. Decreased AsA and GSH.	[152]
B. napus cv. Suyou No. 1	100 mM NaCl; 2, 4, and 6 d	γ-glutamic acid; 20 mg L^{-1}	Added with nutrient solution	Increased DW. Enhanced K^+/Na^+ ratio, Pro and antioxidant enzymes activity.	[49]
B. juncea cv. Pusa Jai Kisan	100 mM NaCl; 30 d	Ethephon; 200 ml L^{-1}	Foliar spray	Reduced leaf Na^+ and Cl^-. Increased N content and NR activity. Declined 1-aminocyclopropane carboxylic acid synthase activity and ETH evolution.	[69]

Species and cultivars	Stress exposure	Elicitors and dose	Application method	Effects	References
B. carinata cv. Adet and Merawi	50, 100 and 150 mM NaCl; 28 d	SA; 0.5 mM	Foliar spray	Increased RWC, F_v/F_m, g_s, P_n and T_r and NR activity. Increased growth parameters, biomass and Chl content.	[41]
B. juncea cvs. Varuna and RH-30	78, 117, and 156 mM NaCl; 120 d	24-EBL; 10^{-8} M Pro; 20 mM	Foliar spray	Increased SL, FW, DW, and LA. Reduced EL. Enhanced RWC, SPAD, P_n, g_s, C_i, and CA activity. Increased seed yield.	[42]
B. napus cv. BARI Sarisha-13	100 and 150 mM NaCl; 48 h	β-aminobutyric acid (BABA); 150 μM	Seedling pretreatment	Decreased Na^+ and enhanced K^+. Improved plant height, FW, DW, RWC, Chl *a* and Chl *b*.	[65]

Table 10.
Supplementation of different chemical elicitors to inhibit the adversity of salt stress in Brassica sp.

Application of SA (1 mM) and 24-EBL (0.1 μM) in salt-treated mustard improved the contents of anthocyanins, phenolics, flavonoids, Chl *a*, Chl *b*, and Car and also reduced lipid peroxidation by enhancing antioxidant activities. Whereas foliar spraying of GA_3 increased P_n, g_s in salt-stressed *Brassica* sp. [155]. Siddiqui et al. [155] also found reduced MDA content, EL and increased activity of NR and CA in the salt-stressed plants.

Other inorganic and organic chemical elicitors are also used to induce the salt tolerance in *Brassica* plants. Application of NO alleviates salt stress in *Brassica* crops through enhancing P_n, g_s, C_i, NR, and CA activity compared with the non-saline control plants [15]. Beside this, Sami et al. [14] also sprayed glucose (4%) to ameliorate the salt stress in *Brassica* sp. and found profound increase of growth, photosynthetic and antioxidant enzyme activities. Further, Xu et al. [156] reported that pretreatment with poly-γ-glutamic acid (γ-PGA) enhanced salt tolerance of *B. napus* by improving Pro accumulation and increased total antioxidant capacity. Application of γ-PGA also inhibited the content of the oxidative stress indicators (MDA and H_2O_2), thus enhancing growth and development of plants [156]. Thus, scientists have evolved plenty of ways to mitigate the adverse effect of salt stress in oilseed *Brassica* sp. cultivation and found some efficient approaches to increase the yield by minimizing the oxidative damages and improving defensive responses.

5. Concluding remarks

In the past few decades, salt stress in plants has been widely studied in many crops. As oilseed *Brassica* is an important oil crop, therefore, the production of this crops in the salt-affected areas should be explored. There are numerous genotypes of *Brassica* available globally. Therefore, screening the genotypes would be a very first line of work by breeders and plant biologists. As a model plant, *Arabidopsis* has been widely studied by researchers and many salt tolerance traits have been revealed. Moreover, genetic and molecular bases of salt stress tolerance is underway. Salt stress-induced overgeneration of ROS and subsequent oxidative stress is a common phenomenon in any plants. Understanding the basis of antioxidant defense including ROS signaling and other signaling cascade should be fine-tuned in the light of plant responses to salt stress. Moreover, the approaches should be applicable in the field. Recently, exogenous application of biostimulants, phytohormones, plant nutrients, and many stress elicitors has been researched and applied on the oilseed *Brassica* plants to enhance salt tolerance. However, their appropriate doses and application methods should be fine-tuned. An integrated approach involving agronomy, plant physiology, and genetics is needed to avail such outcomes.

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Conflict of interest

The authors declare no conflict of interest.

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Chapter 4

Soil Amendments: An Ecofriendly Approach for Soil Health Improvement and Sustainable Oilseed Production

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Abstract

Oilseed crops are major part of human diet providing energy, used for cosmetics, health supplements and other purposes. Intensive agricultural practices, overexploitation of natural resource and climate change pattern have adverse impact on soil health, thus becoming serious concern for oilseed crop production and livelihood security of farmers. Maintenance of soil health with amendments can restore, revitalize and regain the soil quality for sustainable agriculture. Soil amendments, therefore have definite advantage by improving soil health and facilitating nutrient supply to oilseed crops. Soil organic amendments such as animal manure, compost, vermicompost, biosolids/sewage sludge, biochar etc. and inorganic amendments such as gypsum, zeolite, pyrite etc. are the most commonly available amendments which can be directly applied to soil after treatments. Direct and indirect effect of soil amendments on soil chemical, physical and biological properties significantly influences soil-plant-continuum, beneficial for soil health improvement, carbon sequestration and oilseed yield improvement. Soil organic amendments could substitute nearly 25–50% of synthetic fertilizers, enhance nutrient use efficiency and influencing oilseed yield response. Soil amendments may sustain or increase oilseed productivity at reduced production and environmental cost, thus, improve soil health and water use efficiency and its quality, and mitigating climate change impact.

Keywords: gypsum, organic amendments, oilseed crops, soil properties, yield response

1. Introduction

Soil degradation is the major obstacle for sustainability of crop production and human survival. With deteriorating climate change effects, of erratic rainfall patterns, sudden increase in rainfall intensity and temperature fluctuation around the world is a serious challenge for farmers, environmentalists and common man.

Increasing pressure of human population, that has been estimated to rise up by 9.5 billion by 2050 would increased rastically food demand [1]. Food insecurity due to changing climate change vagaries and increasing population pressure is challenging scenario for researchers and policy makers. Furthermore, nutrients bioavailability, environmental factors as well as the biological soil health are other important criteria for improving crop yield per unit area for achieving the targeted goal of food security. Agriculture management strategies for improving crop growth and yield is usually achieved with genetic manipulation higher fertilizer doses, faulty irrigation practices, pesticides, weedicides etc. [2, 3]. Subsequently, few management techniques led soil health deterioration due to low soil organic matter, micro-nutrient or specific nutrient deficiency, biodiversity loss, persistence of chemicals in soil system etc. These factors are responsible for soil/land degradation which is a major problem for declining agricultural productivity [4]. Soil degradation adversely influence soil properties by productivity losses directly hampering human needs and capacity to perform various crucial service and functions, which are valued between US $1610 to US $19,420 ha^{-1} y^{-1} in organic farms and between US $1270 to US $14,570 ha^{-1} y^{-1} in conventional farming system [5]. Therefore, there is an urgent need to reverse soil degradation and improve soil properties to recover soil health in sustainable manner. Sustaining crop productivity and soil quality by site specific management strategies is essential, to conserve natural resources for the future generations.

Soil health improvement is pre-requisite for sustaining soil health and crop productivity. Agricultural management practices can reduce delivery of normal ecosystem services and functions, for instance by intensive use of chemical fertilizers and pesticides can increase nutrient losses, polluting water bodies (eutrophication) and aquatic organisms [6]. This could incur additional cost on water purification, decrease the esthetic and recreational values of water reservoirs. Thus, alternative solutions for reducing dependency on costlier chemical inputs in agricultural could be long term solution for maintaining and restoring soil fertility. Addition of organic and inorganic materials so as to improve soil properties so as to sustain crop production is a process of amending the sick soils. A healthy soil in arable system constitutes a good balance of organic and inorganic components. Such soil are usually characterized by higher biodiversity and lower concentration of inorganic and organic nutrients [7]. Rejuvenating soils by amendments with easily available products and environmentally safe is essential for improving soil health conditions. Soil amendments used as soil conditioners tom improve physical, chemical and biological properties so as to enhance crop productivity and livelihood security of farmers. The organic managed fields, with no application of chemical fertilizers and pesticides, are closer to natural soil than conventional fields, where soil fertility is maintained by consistent application of organic amendments. Generally, addition of organic amendments such as FYM, composts, animal manures etc. significantly increases SOC, on contrary to chemical fertilizers which have opposite effect [8, 9]. Biochar are carbon rich stable inert compounds produced from biomass pyrolysis that enhances soil carbon, positive impact on soil properties, crop yield and environment, are included in agroecosystem over a decade or two [10, 11]. Crop diversification by including oilseed crops (soybean, groundnut, mustard, sunflower etc.) in rotation or intercropping in conventional farming system are better options for withstanding climatic conditions, reducing irrigation and costlier agrochemicals, natural resource conservation, environmental safety and ensuring livelihood security of farmers [12].

Oilseed crops are the fourth most important category of agricultural produce globally next to cereals vegetables, fruits and nuts [13]. Oilseed crops contain triacylglycerol content making them important energy source containing bioactive compounds such as phytosterols, fat soluble vitamins, carbohydrate, phenols etc. [14]. Oilseed crops can be annual such as soybean, mustard, sunflower, groundnut, castor etc. and can be perennial such as coconut, oil palm, olive etc. Among oilseed crops, soybean and rapeseed/ mustard are the most globally produced oilseed crops [14]. Oilseed crops also known as vegetable oils is the most preferred crop as they are easily available, economically cheap and are cultivated in various agroclimatic regions around the world [15]. The bumper oilseed production during 1990 lead to 'yellow revolution' in India, however, could not sustain for longer period. Oilseed crops have the potential of improving productivity and profitability in various oilseed-based cropping systems. Unlike cereal crops, oilseed crops most grown under rainfed conditions are more tolerant to harsh weather conditions. However, few oilseed crops have higher market price, wider adoptability and provide optimum yield under stress conditions [12]. Poor nutrient management, excessive use of sulfur free fertilizers, micronutrient deficiency, salinity stress, moisture deficit, etc. are some major constrains in oilseed production. Soil nutrient mining and water depletion is the two most important constraints in oilseed production followed by pest and disease [16]. Soil management with soil amendments could be a helpful technique in improving oilseed yield and quality without deteriorating soil health. Application of chemical fertilizer or organic manure alone cannot sustain oilseed production. Therefore, judicious use of organics with inorganic fertilizers are essential to augment productivity, input use efficiency and soil health protection. Efficient management practices of oilseed crops includes higher production and processing oil with improved technology governs the economic health of the country. In India, oilseed crop is the second most category after cereal crops governing the agricultural economy, growing at 4.1% per annum during last three decades [17]. Most commonly grown oilseed crop includes soybean, rapeseed, canola, groundnut, sunflower, oilpalm, coconut, olive, cottonseed etc. Oilseed crops are known for their oil quality and quantity (yield) which determines the consumers choice and farmers profitability. Oil quality is characterized by its chemical components which includes, fatty acid, active compounds, microelements, vitamins and flavoring substances [18, 19]. Beside these components, oils are rich source of vitamins like A, D, E, K, in which vitamin E with antioxidant properties can remove free radicals in cells that can cause aging and cancer [14].

2. Oilseed area and production

Globally among oilseed crops, largest production is recorded in soybean followed by canola/ rapeseed, sunflower, groundnut, cottonseed, oilpalm and copra. Some of the common oilseed crops, their oil content and uses are explained in **Table 1**. During the year 2021–2022, soybean production was 364 metric million tonnes. On consumption level, soybean oil is the most preferred, followed by canola and oilpalm [20]. Among vegetable oils, palmoil records highest annual yield and is continuously increasing in the recent years. South-Asian countries like Malaysia and Indonesia contributes to 85% of production. Soybean followed by rapeseed is the next important oilseed crop with higher yield [14]. Major producers of soybean includes China, USA, Argentina, Brazil etc. Countries like China, Canada, EU are major producers of mustard crop during 2017–2018. China and India are major producers of groundnut oil. Sunflower is a major oilseed crop in Ukraine, Russia and EU. South East Asian countries, Philippines are major producers of coconut oil. Approximately, 25 million hectares globally is

Oilseed crop	Family	Oil percentage (%)	Type of oil	Uses
Soybean	Fabaceae	18–24	Vegetable oil	Protein source, Cooking oil, Flour, Pharmaceutical industry
Rapeseed	Brassicaceae	37.5–46.3	Vegetable oil, Diesel oil	Animal feed, Biodiesel
Peanut	Fabaceae	46–57	Cooking oil	Cooking, Cosmetics, Dyes, Textiles, peanut butter
Sunflower	Asteraceae	46–50	Seed oil	Cooking oil
Palmoil	Arecaceae	50–55	Vegetable oil	Cooking oil, Cosmetic industry; Detergent
Coconut	Arecaceae	65–74	Vegetable oil and biofuel	Cooking oil, Cosmetic and Food industry; Chocolate Beverages, Vinegar
Sesame	Pedaliaceae	43–61	Vegetable oil	Cooking oil
Cottonseed	Malvaceae	15–40	Seed oil	Detergents, Cosmetic industry; Insecticides
Safflower	Labiatae	About 40	Vegetable oil	Cooking oil
Olive	Oleaceae	31–56	Cooking oil	Cooking oil
Castor	Euphorbiaceae	30–50	Vegetable oil	Additive in food Skin care products Biodesel
Niger	Asteraceae	37–47	Vegetable oil	Cooking oil As medicinal use in Asthma and reducing inflammation

Source: [14, 19].

Table 1.
Major oilseed crop and their uses.

Edible oil	Global production (million MT)	Major oilseed producing countries
Palm oil	73.49	Malaysia, Indonesia,
Soybean	56.97	USA, Argentina, Brazil, China
Rapeseed	27.96	European union, China, Canada
Sunflower	19.45	Ukraine, Russia, EU
Groundnut	5.57	China, India
Cottonseed	4.09	China, USA, India, Egypt, Uzbekistan
Coconut oil	4.09	Philippines, South-east Asian countries
Olive oil	2.04	Spain, Italy, Greece, Turkey

Source: [14, 24].

Table 2.
Oilseed producing countries and their production worldwide.

under sunflower cultivation, accounting for almost 8% of world oilseed market [21]. Mediterranean countries Spain, Greece, Turkey accounts for 90% olive oil production worldwide [14]. India is the second largest consumer after China in vegetable oil consumption for food. Countries like Argentina, United States of America and Brazil are the major soybean exporters to India and China. However, in the recent year of 2021–2022, soybean oil imports in these countries are slowed down due to higher prices of soybean oil and shift towards other oilseed crops like rapeseed especially in India. The record harvest of rapeseed crop in India during 2021–2022, forecast the bumper production of 800,000 tons can reduce the import of oilpalm and sunflower [22].

According to an estimate by USDA [22] India consumes nearly 21.8 million tons of oilseed in 2021–2022. Among oilseed crops, highest vegetable oil for food use followed the order, oilpalm> soybean> rapeseed> sunflower> other oils during 2017–2018 to 2021–2022. India and China are major vegetable oil importers to meet their domestic demands. Globally, India being the fifth largest oilseed economy accounting for 7.4, 5.8, 6.1and 9.3% in oilseed, oil, oil meal and edible oil consumption respectively [23]. Global production of edible oils and major exporters and importers are given in **Table 2**.

3. Soil amendments for soil health improvement

Sustainable crop production and improving soil quality is a major concern which need development of management strategies without negative effect on environment can lead to food security and natural resource conservation. In this approach, soil organic matter plays indispensable role which is directly related with soil ecosystem services and functions for long term oilseed productivity. Soil management for sustainable agriculture can be achieved by improving soil organic matter/ organic carbon of soil through organic amendments addition to soil at regular time intervals. Thus, soil organic matter will help to conserve or restore soil fertility to meet present and future food requirement, with acceptable impact on environment [25, 26]. Soil health is directly related to soil and crop productivity and is being recognized as a major component for mitigating climate change effect and food security. Soil health is closely associated with soil quality, in which the biological health of the organism in soil is critical for soil resiliency and ecosystem services [3]. Constant decline in soil health post green revolution in many countries are growing challenge for stakeholders to sustain oilseed productivity. Inorganic fertilizer application is effective to increase oilseed yield might be short term, but require long term additions. Increasing cost of chemical fertilizers are uneconomical for marginal farmers and creating environmental problems. Therefore, its essential to select locally available organic resources that are easily available, eco-friendly and at reasonable price for farmers application. Based on a recent report by Shukla [27], based on soil sample collected from various Indian states, indicated soils were deficient in sulfur, Zn, Fe, Cu, Mn and B by 41, 43,14.4, 6.1, 7.9 and 20.6% respectively. In soybean and mustard growing belt of North India, most soils are deficient of S an essential nutrient determining oil quality and productivity. Inadequate and imbalanced nutrient management in oilseed crops results in multi-nutrient deficiency in crops and arable soils. Therefore, integration of soil organic amendments for improving soil health by applying various organic

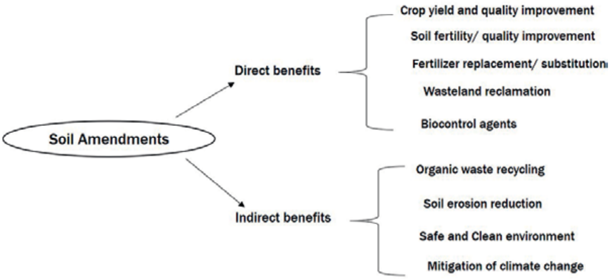

Figure 1.
Potential benefits of soil amendments.

sources includes, FYM, compost, vermicompost, biofertilizers, municipal solid waste, agro-industry waste etc. Addition of such organic amendments to soil will not only improve soil fertility, but would improve physical properties and enhance microbial activity and plant growth [28, 29]. Direct and indirect benefits of using soil amendments are illustrated in **Figure 1**. Soil amendments acts as soil conditioners by alleviating stress, improving soil properties and fertility, enhances ecosystem services and human health, showing minimum impact on environment.

Stagnation in oilseed crop yield in many areas of the world has been attributed to suboptimal supply of nutrients, poor or no application of organic manures, negligible use of soil amendments, erratic rainfall pattern etc. Soils with low organic matter coupled with low native P, sulfur deficiency and micro-nutrient unavailability are some of the major constraint limiting oilseed yield. Best nutrient management practices, therefore, include integration of organic amendments with recommended chemical fertilizer doses to supply macro and micro nutrients to facilitate crop nutrient demand. Integrated nutrient management signifies the role of organic amendments in partially replacing inorganic fertilizers will not only supply essential macro and micro nutrients to crops but would regulate, water, air, temperature, nutrient transformation and biological activities [26]. Major challenges for maintaining sustainable crop production involves use of tools and techniques to enhance agricultural productivity ensuring food security, with minimum disturbance to environmental systems. Many ecological interventions have been addressed to improve the delivery of ecosystem services and functions, by reduce anthropogenic inputs in agriculture. With more emphasis on circular economy paradigm shift, decreasing the dependency on external inputs, reuse, recycling of the available resources at farm aimed at preserving and protecting soil ecosystem. Soil amendments could thus be effective strategy in gaining momentum towards natural or organic farming replacing costlier chemical inputs. Organic amendments such as manures, crop residues (CR), composts, green manures, biosolids, agri-processing industry wastes, industrial slurries etc. are usually applied to soils either as fertilizers or used for ameliorant and remediation purposes [30]. Biofertilizers commonly known as microbial consortia's or micro-organisms are beneficial microbes used for improving soil health and productivity. They are also included under organic amendment category known as biofertilization techniques [31]. Soil health is defined as the capacity to perform various functions to support plants and organisms. Recovery, restoration and conservation of soil health is utmost important for survival of living beings. Reviving soil health with use of soil organic amendments is gaining much attention due to its cost-effective and eco-friendly approaches. The potential benefits of soil amendments on soil properties are shown in **Figure 2**.

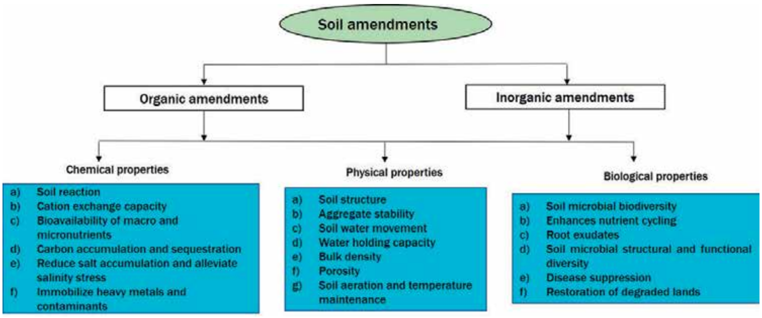

Figure 2.
Soil amendments influence on physical-chemical and biological properties of soil.

4. Types of soil amendments

Soil amendments are generally added to soil for reclamation process which improve soil physical, chemical and biological properties. Soil amendments can be inorganic and organic resources. The most preferred soil amendments include natural minerals like gypsum, pyrite, lime; other amendments from biological origin such as animal manures, compost, vermicompost, farm yard manure etc. are organic in nature. Organic amendments generally used in arable lands are derived from agriculture, forestry sources and urban areas. In agriculture, animal manure is the most common source of amendments from animals, like cattle, buffalo, goat, poultry etc. Inefficient utilization of nutrients (viz., N, P, K, etc.) and rainwater by oilseed crops are mostly associated with low soil organic matter [32]. Therefore, addition of organic amendments stimulates microbial activity which releases organic acids and other metabolites that reduce nutrient sorption and enhance availability of nutrients (P, K). Addition of inorganic amendments such as gypsum, clays like bentonite, perlite etc., lime, sodium chloride, epsom salt, sulfur minerals etc. are allowed in soils reclamation with some restriction and are mostly based on site specific management practices. Thus, the two most common soil amendments used in agriculture are described below.

a. *Organic amendments*: Organic amendments are usually derived from live sources and natural sources of carbon for micro-organisms. Soil organic amendments are generally derived from variety of sources such as plant origin, animal manures, crop residue or waste parts, green manures, forest system, urban wastes, agro-processing wastes etc. Among these the most common organic amendments used in agriculture consists of animal manure which can be fresh, composted, liquid or solid fractions etc. from various animal species. Other organic resources include crop residues such as straw, grain husk, legumes, sometime mushroom spent wash. Forest origin amendments mostly includes, wood shavings, wood chips, sawdust, deink sludges, leaves etc. Industrial wastes such as coir-pith waste, sericulture waste is known to tremendous amount of nutrient content. Urban wastes mostly includes the organic fraction of municipal solid waste, sludge waste, industry waste are rich source of nutrients but are used with restriction as organic amendments in crop fields [33]. Interestingly, biochar is yet another and famous organic amendments gaining popularity in agriculture and other fields. Addition of microbial inoculants or biofertilizers are effective amendments for improving oilseed production by enhance biological N fixation in legume oilseed crops, uptake of nutrients, efficient utilization of water directly influencing yield. Treating legume oilseeds with rhizobia and P fertilizers improved soybean grain yield because P availability enhances N assimilation from atmosphere by root nodules [34].

b. *Inorganic amendments*: Inorganic amendments are either mined or man-made in nature. Inorganic amendments most commonly used as soil conditioners are lime and gypsum. Beside these, basic slag, sulfur, perlite, bentonite clays, Epsom salt, sodium chloride, etc. are other inorganic source of amendments. These minerals naturally occur in earth and can be used to improve soil physical chemical and biological properties especially by adjusting soil pH. Amendments such as gypsum are commonly used to rehabilitate saline-sodic soil supply S nutrient and alleviate salt stress. Gypsum is oldest soil amendment, important source of Ca and S commonly used for crops. Besides natural mine gypsum, flue gas desulfurization (FGD) gypsum is also used as soil amendment available as by-product from coal-fired power plant to remediate saline-sodic soils [35].

4.1 Commonly used soil amendments in agriculture

Utilization of organic amendments as soil conditioner/ fertilizers though is old, but increasingly become popular worldwide not only to reduce chemicals but are a sustainable, eco-friendly approach. Soil amendments such as manures, compost, mineral/organic fertilizers, biochar, biosolids, microbes etc. generally improve plant growth and soil health [8, 36]. Reutilization of organic waste is also socially acceptable approach which could be better substitute to landfills, incineration and directly contribute to SDG goal 3 (Good health and wellbeing) and 6 (Clean water). Moreover, to combat soil degradation, a circular economy concept is a sustainable approach which had recently gained global attention. Organic farming could rejuvenate, and restore soil health, thus improving soil productivity by altering physical, chemical and biological properties. In this chapter, therefore, more emphasis is given to the role and importance of organic amendments on oilseed crops. Farmers are therefore, encouraged to integrate organic amendments in their farming system which can reduce chemical input cost and improve soil quality for long term cropping. Some of the commonly used organic amendments/ manure used in agriculture are described as follows.

a. *Animal manures*: Animal or livestock manures are the easily available organic amendments and used by man since decades in agriculture. Major limitation with use of manure is due to their large volume, bulky nature, high moisture, and transportation cost. The quality of manures in terms of nutrients and other components depends upon the feeding stock, animal type, quantity of dung or litter produced, their management practices etc. Poultry manure are considered rich source of nutrients compared to animal manure. Cattle manure on dry weight basis is characterized by 0.56–4.24% of ammonia N, 1.18–2.9% of organic N, 42 ± 6% of Carbon and 11.7 ± 5 C:N ratio [37]. Integration of animal manure with chemical fertilizers increases soil organic carbon, thus maintaining soil fertility for longer time.

b. *Composting*: Composting is the most common sustainable technique of oxidative disintegration of biomass with micro-organisms. Composting provides good quality end products which are cost effective, environmentally safe and enhances crop production. Animal manure composting is an effective method of nutrient enriched stable compounds, decreased mass and water content, supressed weed seeds and pathogens etc. The quality of compost obtained depend upon various factors such as the feedstock, aerobic/ anaerobic decomposition, heavy metal content etc. Therefore, to improve efficiency of composting addition of various additives such as zeolites, biochar, clay minerals, phosphate sources, gypsum, micro-organisms etc. are used for crop production.

c. *Vermicompost*: Composting techniques in which earthworms are used for degrading and accelerating biodegradable substances is vermicomposting. The most commonly used species of earthworm are *Eisenia fetida*, and *Lumbricusrubellus* are the most efficient species. Compared to normal composting, vermicomposting is faster due to worm activity producing compost rich in nutrients and plant growth regulators.

d. *Crop residues*: Most of the developing countries generate more than 1000 million tonnes of crop residues, which is either burnt in-situ or part of it utilized as animal feed, or other purposes. These CR if recycled properly in fields can significantly contribute to organic carbon and essential nutrients. CR recycling along with animal manure and fertilizers are economical and environment friendly approaches to improve soil health and decrease dependency on chemical fertilizers. Plant stover/ straw is a major source of humus, and lingocellulosic waste generated, traditionally use as soil amendments and also raw material for composting process.

e. *Biofertilizers*: Biofertilizers are considered green technology and eco-friendly alternative strategies to fertilizers which can improve plant nutrition and soil health under oilseed-based cropping system. Use of microbial inoculants or consortia of micro-organism that promote plant growth by enhancing uptake and bioavailability of mineral nutrition. Combine application of microbial inoculants are known to give better results compared to single microbial species. Biofertilizers include plant growth promoting microbes by direct and indirect process such as biological nitrogen fixation, phytosiderophores, chelates, sugar/ root exudates, hydrolytic enzymes, hormones etc. which increase bioavailability of nutrients to crops. Chelates released by crop roots complexes with micronutrients such as Zn, Fe improving their solubility and enrich crops with micronutrient content. Plant growth promoting organisms such as Azotobacter, Azospirillium, Rhizobium, Pseudomonas, Trichoderma, Flavobacterium, Streptomyces etc. are important biofertilizers utilized for enhancing crop growth and yield. Seed biopriming, increasing N and P availability, with biofertilizers will have positive influence on yield and yield components. Compared to chemical fertilizers, biofertilizers supply essential plant nutrients, reduces leaching losses and improve nutrient use efficiency. Few biofertilizers recommended for oilseed crops include: (i) Rhizobioum for soybean and groundnut; (ii) Azotobacter for sunflower, safflower, mustard and sesame; (iii) Arbascular mycorrhizae for soybean and sunflower; and (iv) Bacillus for K and Zn solubizers for all crops [38]. Soils amended with microbial consortium thus, enhances crop growth and yield, enhance nutrient uptake thereby reducing the negative impacts of chemical fertilizers.

f. *Biochar*: Biochar is carbonaceous material produced by heating different biomass at various temperature range under limited oxygen supply for stipulated time. Biochar strongly adsorbs ammonia, phosphate, potassium through functional group, reduce N emission, leaching losses, niche to various micro-organisms. Biochar use as slow fertilizer release components to improve nutrient use efficiency and reduce losses. Biochar is one of most appreciated soil amendments for its potential carbon sequestration capacity, nutrient supply, water holding capacity, aeration, enhanced microbial activity etc. [10, 39] resulting in overall soil health improvement. Compared to biochar alone, combined application of biochar with fertilizer or organic manures/ compost proved better nutrient use efficiency, improved soil properties resulting in better crop yields [36].

g. *Municipal solid waste (MSW)*: Sewage sludge from waste water treatment plants are applied to soil as organic amendments. Approximately 50–70% of biosolids produced is applied to land in these countries. Biosolids or treated sewage sludge are easily available and cheap source of nutrients such as N, P, K, micronutrients and organic matter. Thus biosolid application can improve soil quality by increasing soil fertility and could be safe disposal of treated sludge. However, biosolids contains sometimes heavy metals, or other pollutant and pathogens. Therefore, potential risk associated with application of such amendments should be carefully analyzed before direct application to soils to prevent contamination of soil and water.

h. *Organic wastes from agro-industries*: Large quantities of organic waste are generated from vegetable markets, agro-based industries, food-based industries, sugar industries etc. Sugarcane bagasse, pressmud, paddy husk, oil waste, jute waste, groundnut shell, cotton stover, tea, fruit pulp waste etc. are different sources of waste generated during processing. Some agro-waste are composted and used as soil amendments showed significant improvement in crop yield. Sugar industry waste such as pressmud is used along with gypsum to alleviate sodicity problems in semi-arid regions [40]. Major constrain with the usage of such organic resources are the transportation costs and environment problems such as presence of heavy metals, pathogens etc.

i. *Other organic amendments*: Other amendments such as coirpith, seri-waste, tank silt etc. are available as location specific materials for agriculture usage. Coir-pith waste is generated as by-product of coir industries that decomposes slowly due to complex lingo-cellulose complex and are known to reduce soil erosion and enhance water holding capacity [41]. Sericulture waste on otherhand is silkworm litter enrich with nitrogen (280–300 kg), phosphorus (90–100 kg) and potassium (150–200 kg) and more effective than conventional FYM manure [41]. Hence such organic waste can be recycled back to soil to enhance its health.

j. *Inorganic amendments*: In oilseed crops gypsum, pyrite etc. are the common soil amendments used due to high S demand, which influence crop yield by 10–48% in irrigated and 25–124% under dryland conditions [42, 43]. Gypsum improves soil conditions with better root expansion, exploring more volume of soil, reducing sub-surface Al toxicity, better nutrient and water utilization etc. with positive yield response [44]. Zeolite play important role in improving physical property of soil, increase cation exchange capacity, and reduce N leaching [45]. Zeolite is thus considered as an efficient soil amendment in retaining water and essential nutrients in crop root zone [46].

Amendments	Availability	Uses	Advantages	Disadvantages
Animal manure	Higher availability; Sustainable supply	Fuel, fertilizer, organic matter (OM) source	Multiple uses; versatile soil amendments	Bulky nature; large volume; loading and transportation problems;
Compost / Vermicompost	Location specific; Availability varies; Competing users	OM source; organic fertilizer for crops	substitute to chemical fertilizers; stable product	Low availability; price fluctuations; low N availability compared to manures
Green manures and crop residues	Location and site-specific	OM and nutrient source	Addition of biomass, organic matter, Nitrogen and other nutrients to soil	Availability of GM seeds; CR could impact tillage operations; High C:N ratio of CR can immobilize nutrients
Biosolids	Surplus availability in urban areas; continuous supply	Organic matter source; essential nutrient source	Multiple uses as amendments; cost effective	Heavy metal and harmful pathogen hazard; High nutrient build up in some location causing pollution
Industrial waste	Site-specific	OM and nutrient source	Cost effective, multiple uses as amendments	Contaminants/ pathogen; transportation cost
Digestate	Highly location specific; limited availability	OM and nutrient source		Variable quality; not fully characterized; odor problem; pose pathogen problem
Biochar	Not easily available	OM source; soil amendment; increasing soil pH	Conversion of biodegradable waste into stable carbon product; improves carbon sequestration; used as liming material; good filtration method for waste water and polluted soils	Initial investment; availability of raw material; complex mechanism
Inorganic amendments				
Gypsum	Locally available; industrial by-product	Calcium and sulfur source; versatile soil amendment for salt affected soils;	Easily available, economically feasible; good source of S for crops	Source of gypsum might vary sometimes, by-product such as phospho-gypsum could be loaded with contaminants; radioactive compounds

Amendments	Availability	Uses	Advantages	Disadvantages
Basic slag	Location specific; Materials are usually free	Acts as Ca source for acidic soils	Acts as sorbent	Cause NH_3 volatilization
Zeolite	Location specific; Naturally available	Improves soil properties such as cation exchange capacity, water holding capacity and high adsorption capacity	Regulate nutrient availability and enhance fertilizer use efficiency; acts as soil amendment; acts as heavy metal trap; slow release of herbicide; water and gas adsorption	Very costly; Not easily available; Research studies are less

Table 3.
Types of soil amendments for oilseed production.

Soil amendments interacts and modifies soil chemical, physical and biological properties for optimizing oilseed production. However, considerable variability in climate, crop type, management practices, and types of organic amendments significantly impact crop yields. Agronomic evaluation of soil amendments in organic matter supply, plant nutrient availability and soil property modifications determine the potential of amendments in cropping systems. Different sources of soil amendments that can be used for improving oilseed production are explained in **Table 3**.

5. Soil properties as influenced by soil amendments

a. *Chemical properties*: Combined use of organic amendments such as FYM, compost, vermicompost, green manures etc. with chemical fertilizers are essentially required to improve soil health. Addition of soil organic amendments result in carbon accumulation and enhance SOC content in long run for sustaining any cropping system. Organic amendments such as FYM, composts, CR can sustain SOC at higher levels in soil as compared to mineral fertilizers. Soil organic amendments effect pH and cation exchange capacity, which indirectly influence essential nutrient bioavailability thereby direct impact on soil fertility [47]. Composition and maturity of soil amendments significantly influence soil reaction. Some amendments have high Ca or basic cations which results in 'liming effect' of soil thus increasing soil pH [48]. Thus liming improves soil microbial activity and diversity in acid soils. On contrary some organic amendments reduce soil pH which is attributed to either humic acids released during carbon pool degradation and /or by nitrification of ammonium in the amendment [49]. Blanchet et al. [50] reported that addition of FYM and CR amendments with reduced mineral fertilizers improved SOC by 6.2 and 2.4% respectively over only fertilizers plots after 50 years of cropping. Application of these organic amendment improved C/N ratio, available P and K content. In soybean crop, addition of 5 t ha^{-1} FYM with RDF increased grain yield by 13% over the control [51]. Improvement in crop yield with organic amendments application could be attributed to increased N supply directly and indirectly improving soil environment for plant growth. Organic amendments such as FYM, animal manures etc. contain varying amount of N, P, K and other nutrients. Among nutrients, N amount and availability is associated with the type of organic amendments added to soil which undergoes mineralization to provide available N to crops. Organic manures or compost supply N, but slow mineralization by micro-organism limits its availability in short-term. However, with continuous application of FYM, compost etc., builds up N and residual effect on N availability is usually visible after 4–5 years [25]. Depending upon the origin and type of organic resources, variable effect is observed on soil pH. Long term application of organic amendments was found to decrease [52] and increase [53] soil pH in many studies. Chemical properties like cation exchange capacity improves with addition of FYM, biosolids etc. Beneficial effects of FYM and phosphocompost with recommended fertilizer doses in soybean crop on significant improvement on SOC, N, P, K and S availability in vertisol has been reported by many researchers [54]. Organic amendments regulate P and K supply by (i)chelating with Al, Fe, Ca ions thus decreasing precipitation of P and enhancing P availability; and (ii) reduce K fixation, solubilization and release slowly K by organic-clay interactions. Application of biosolid-municipal waste compost once in 4 years improves P supply in soils [55]. Beside enhancing nutrient availability, soil amendments viz., organic manures/ compost improve rain water use efficiency of oilseed crops by increasing moisture retention capacity of soil [56].

b.*Physical properties:* Soil amendments, both organic and inorganic alter soil physical properties supporting both chemical and biological parameters in improving soil health. Organic amendments, in particular improves soil structure, better soil aggregation, enhance water holding capacity, maintains optimum soil temperature, reduces bulk density (BD), increases porosity favorable for extensive root growth and development to extract plant nutrients. Moreover, organic amendments stimulate microbial activity, secretion of exopolysaccharides improve soil structure, other compounds like hyphae enhances soil aggregation and stability. Addition of FYM with fertilizer dose, decreased BD significantly compared to only fertilizer plots [57]. This decrease in BD is due to higher pore space, organic carbon, better aggregation, root growth, and micropores in soil amendment treated fields. Application of soil amendments/ conditioners significantly decreases soil bulk density and a decrease in bulk density would be expected when soil is mixed with less dense organic material. Addition of municipal solid waste compost improved water stable aggregate and macro pore distribution, leading to higher hydraulic conductivity of clay loam and loamy sand soils. Microbial respiration improvement with addition of MSW compost directly improved soil structural and hydrological properties [58]. In addition, soil rich in organic matter are less prone to erosion processes than soils with low organic matter those that are predominate in arid and semi-arid areas, the reason being organic matter improves soil structure and tilth as well as it cements individual soil particles into larger aggregates, which leads to less runoff and erosion. The amendments can increase the stability of surface soil aggregation, which has ability to resist movement by wind or water and soil pores created by aggregation promotes water infiltration, thereby reducing runoff and transport of soil particles with the water, indicating lower soil erosion. Use of agricultural gypsum is one of the alternative to reduce soil density, on reaction in soil solution it acts as a binder by the cations such as calcium and sulfur, which acts to neutralize soils [43]. Crop residues amendments acts as surface mulch, decreasing evaporation and enhancing water retention in soil. When incorporated, CR acts as carbon source enrich soil organic matter, improves soil aggregation, improves water infiltration thereby reducing soil erosion. Addition of 3 t ha^{-1} mustard CR with gypsum amendment reduced runoff and soil loss by 26 and 29% respectively in soybean crop [59]. CR retention on soil surface benefits (i) protecting bare soil surface against raindrop slashing; (ii) enhancing aggregate stability; and (iii) prevents compaction of surface soils due to rain drop effect [60]. In another study by Soinne et al. [61] reported biochar addition improved aggregation of clay textured soils reducing negative impact of tillage on soil aggregates.

c. *Biological properties:* Soil microbes are crucial components for sustaining soil health as they have affirmative role in enhancing nutrients availability by nutrient cycling through the processes of mineralization and immobilization [62]. Addition of organic amendments improve biological properties by stimulating microbial growth, energy, nutrients, indirectly promoting crop growth and development. These amendments bring biodiversity leading to functional changes promoting plant growth and disease suppression. Furthermore, enhancing structural and functions biodiversity reinforce soil ecosystem, which could become tolerant to natural and anthropogenic stress and turmoil [63]. The presence of active, abundant and diverse microbial community in the soil is an important indicator of improved soil health and agronomic production. Moreover, the activity and abundance of diverse soil microbes govern the stability and function of agro-ecosystems. The activity of soil enzymes is a measure of soil microbial health and is sensitive to various factors including climate, temperature, soil moisture, soil temperature, edaphic properties, crop management practices, etc. [64]. However, the chemical degradation (salinization and alkalization) of soils hinders the biological activities viz. mineralization, enzyme activities, microbial biomass carbon and nitrogen, etc. and lowers the crop productivity. Hence, the application of organic amendments i.e. green manures, crop residues, FYM, compost, vermi-compost, etc. is one of the most suitable management options for degraded soils [64]. The potential benefits of organic amendments in stimulating microbial activities by providing energy and principal nutrients are well recognized [47]. The increased supply of nutrients and growth substrates enhance the numbers of ecological niches and promotes ecological interactions between the microorganisms which may affects the microbial diversity and their abundance [65]. Thus, the increased functional diversity of microbes promotes plant growth, strengthen the soil ecosystem stability and promotes resilience against anthropogenic stresses [63]. The positive role of organic amendments on soil microbial activity, their diversity and composition has been reported in several studies. Organic amendments reduce the soil pH and ESP of the calcareous soil by producing organic acids and increasing the availability of Ca^{2+} which exchange Na^{+} of clay particles and create favorable soil environment for microbial multiplication and activity [66]. The application of sesbania green manure increased the soil microbial biomass carbon (SMBC) by 90%, microbial respiration by 104% and DHA by 265% as compare to control along with the increased C sequestration. Similarly, the application of gypsum improved the SMBC by 29.5% over control [66]. The improved biological activities attributed to increased supply of energy from carbonaceous materials, sugar, amino acids and organic acids produced from the decomposition of organic matter and decay of plant roots. Further, the reduced pH and ESP of soil improved the microbial C into the soil [67]. The black soils are very susceptible to degradation and can be improved by applying gypsum together with organic amendments which improve the microbial activity. It has been recommended that application of organic amendments (green manures) is suitable alternative to costly gypsum for reclamation of sodic black soils, enhancing crop productivity and developing a sustainable agro-ecosystem [66]. The quality and quantity of the organic amendments also influence the diversity and activity of microbial community. Meena et al. [68] reported that application of municipal solid waste compost and rice straw compost at a rate of 16 and 14 t ha^{-1}, respectively significantly improved the dehydrogenase, phosphatase and urease activities than control. The combined use of gypsum and bio-organic amendments (compost and crop residues) provides essential nutrients to crops and improves soil biological properties besides improving physical and chemical properties and productivity of saline soils [69]. The structural and functional diversity of soil microbes and bacterial richness and evenness were improved by application of organic amendments to soil [70]. Thus, the organic amendments have been reported to sustain soil health and crop production by improving soil biological properties. Although, the adoption of soil conditioners/amendments should be based on specific crop production standards for developing sustainable agro-ecosystem [71].

6. Oilseed yield and quality as influenced by soil amendments

Oilseed crop yield and oil quality is influenced by both biotic and abiotic factors. Oil quality is governed by three major compounds namely, fatty acids, triglycerol and bioactive compounds which depend upon crop variety, weather conditions and post-harvest methods [72]. Soil health deterioration with less to no use of organic manures, chemical fertilizers, intensive cultivation, sulfur free fertilizers etc. are major constrains in enhancing oilseed productivity. Sulfur is an essential macronutrient that play important role in protein synthesis, regulates N assimilation inn crops, coenzyme-A, biotin, vitamins etc. and determines oil quality. Oilseed crops are heavy S feeder crops and can remove 10 to 25 kg per year depending upon soil, crop and environmental conditions [73]. Incorporation of soil amendments with recommended fertilizer doses to oilseed crops will have beneficial effect on improving soil physic-chemical and biological properties, improving soil health directly influencing productivity and oil quality (**Figure 3**). Potential yield gap can be minimized by best soil management practices to enhance nutrient availability and uptake by crops. Integrated nutrient management of incorporating fertilizers and organic resources are effective strategy to enhance oilseed productivity. Organic amendments such as compost, green manures etc. acts as slow release organic fertilizers to meet crop demand. Thus, enhancing nutrient uptake by decreasing loss via leaching, runoff, volatilization and increasing nutrient use efficiency.

Soil amendment as nutrient source and soil conditioner can alleviate salinity problems, micro and macro nutrient stress, enrich biodiversity thereby enhancing nutrient supplying capacity of soil. Positive effect of soil amendments such as organic manures, zeolites etc. improved crop yield under water deficit conditions in soybean [74] and sunflower [46]. Soil amendments such as organic manures enhances rain

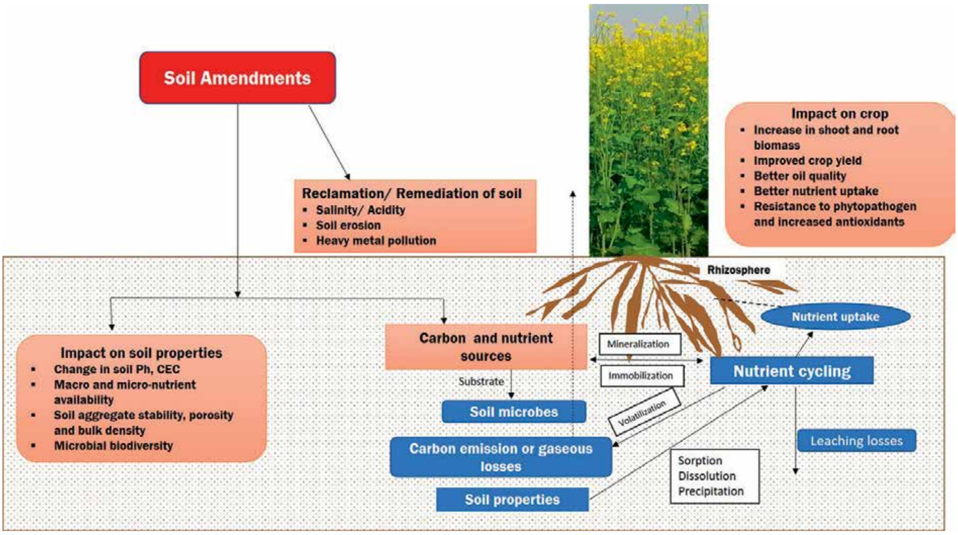

Figure 3.
Soil dynamics and crop performances influenced by soil amendments.

water use efficiency of oilseed crops. According to Adeli et al. [75] organic amendments could increase crop yield by 42% over only mineral fertilizer application. However, crop yield response varies depending upon crop species, soil amendments, edaphic factors and climatic parameters. Ulzen [56] reported that soils treated with rhizobia, P fertilizer and fertisol (manure) showed higher water retention in soil and improved water use efficiency for increasing soybean yield. Organic amendments supply micronutrients, stimulate soil microbial activity and continuously provide nutrients to improve crop yields. Thus substituting chemical fertilizers with organic amendments can be economically feasible and environment friendly approach for sustainable production. Substituting nearly 25–50% of synthetic fertilizers with organic manures/ compost provide better crop yield response and enhance fertilizer use efficiency in oilseed crops. This is due to modification in soil properties such as soil pH, soil fertility, resilience of soil aggregates, soil microbial biomass which enhances ecosystem services and functions, influencing carbon and nitrogen use efficiency. Thus combined application of different types of organic amendments could improve crop yield for long term without deteriorating soil environment. Several studies have shown significant impact of soil amendments on oilseed yield and quality is described in **Table 4**.

Beside the beneficial effect of organic amendments, they also have some detrimental effect on soil ecosystem and human health. The major drawback with application of amendments such as biosolids, sewage sludge, etc. is poor segregation of waste at source that could have hazardous effect on soil environment. Application of immature compost, untreated materials often lead to agronomic and environmental problems. Organic amendments of various types can contain pathogen, pollutants, heavy metals, emerging contaminants such as antibiotic resistance genes, endocrine disruptors, microplastics etc. [33, 92]. Moreover, if unstable organic amendments are applied to land could result in ammonia volatilization, deplete oxygen, release some toxic compounds and immobilize nutrients hindering crop uptake. Indiscriminate and overuse of some amendments might result in environmental pollution by high release of N and P into ground water, rivers etc., eutrophication problems, immobilization of nutrients,

Oilseed crop	Amendment/ treatment	Improvement in yield	Improvement in crop quality	Reference
Soybean	Gypsum, cow manure	Soybean grain yield increased by 44 and 31% with cow manure and gypsum ameliorant in saline soils	Gypsum and cow manure increased leaf chlorophyll content	[76]
Soybean	Poultry litter, Gypsum	Soybean grain yield improved by 42% over control	—	[75]
Soybean	Cattle manure, biofertilizers	Grain yield improved by 132% over uninoculated treatments	—	[77]
Soybean	Rhizobia, organic manure, P fertilizer	Combined application of rhizobia+ P fertilizer + organic manure improved73–93% increase in yield over control.		[56]
Soybean	FYM, Vermicompost, Poultry manure	Higher grain and monetary returns with integration of organic amendments with fertilizers		[78]
Safflower	FYM, Subabul leaves	Maximum grain, straw, petal yield was observed in integrated application of 50% through inorganic and 50% through organic resources.		[79]
Safflower	vermicompost + vermiwash spray + Azotobacter + cow dung urine	improvement in dry matter (3154 kg/ha) and seed yield (1230 kg/ha) of safflower		[80]
Safflower	Gypsum, FYM, Gypsum+FYM	Improved safflower yield in combined application of FYM and gypsum in alkali soils		[81]
Safflower	Vermicompost, Azospirillum, PSB	Safflower yield improved by 19% in vermicompost + biofertilizer treatments Oil content and oil yield improved with organic amendment inclusion with fertilizers.		[82]
Safflower	Municipal waste compost, vermicompost, sheep and cow manure	Improved seed yield with sheep manure (1.67 g per plant) and municipal compost (1.51 g per plant) was recorded. Higher micronutrient uptake by plants was obserd with municipal compost plots.		[83]
Mustard	Sheep manure and humic compounds	Mustard yield improved by 140–190% over control in combined application of sheep manure and humic substances		[84]
Rapeseed	Biochar with urea	Mustard grain yield increased by 16.6% over only urea treatment	Improved NUE 58.8% over urea only	[85]
Mustard	Composted cattle manure (CCM)	Significant yield improvement observed in CCM+ 75 kg N per ha treatment over urea alone	—	[83]
Mustard	10 t FYM + 10 t sewage sludge/ha with fertilizers	Best treatment with 1.73 t/ha yield	Oil content was 37%	[86]
Sunflower	Composted cowdung and gypsum, sole gypsum, sole gypsum	Improved crop yield by 82% with combined amendment application over control		[87]

Oilseed crop	Amendment/ treatment	Improvement in yield	Improvement in crop quality	Reference
Sunflower	Zeolite, organic manure, integrated treatment with different irrigation regimes	FYM (50% or 100%) with zeolite (5 t ha^{-1}) under normal irrigation condition improved biological yield by two times than control	Increased linoleic and olic acid content in organic fertilizer treatment	[46]
Sunflower	FYM, Vermicompost, Azotobacter +PSB	Seed yield improved by 68.1 and 107.5% over control in VC/ FYM+ Azotobacter+PSB + 50% NPK		[2]
Sesame	Compost, chicken manure, FYM with or without reduced N fertilizer	Seed yield improved by 15.9 and 9.7% in chickenmanure and FYM plots respectively over RDF	Oil and protein content improved by 15.1 and 25% in FYM with reduce N application dose	[88]
Groundnut	Biofertilizers (Rhizobium and phosphate solubilizing microbes), FYM	pod and haulm yields of groundnut increased by 40.19 and 35.96 per cent, respectively over no manuring in manuring plots with FYM + *Rhizobium* + PSM		[89]
Castor	FYM, Sewage sludge, Gypsum	Application of FYM and gypsum improved castor seed yield by 4–7% over sewage sludge treatments		[90]
Niger	FYM, Azotobacter	Improved better growth and increased yield by 63% in 75% RDF + *Azotobacter* + PSB or 50% RDF + 5 t FYM/ha treatments		[91]

Table 4.
Oilseed yield response as influenced by soil amendments.

greenhouse gas emission, acidification, salinization etc. [93]. Therefore, safe handling of soil amendments especially from municipal solid waste, sewage sludge, industrial waste etc. is essential for maintaining environmental and human health.

7. Future research gaps

Many studies on soil amendments have highlighted the positive impact of soil amendments viz., manure, compost, biofertilizers, biosolids etc. on crop yield. Gypsum application on oilseed crops has enhanced oilseed yield and quality. However, studies on nutrient release pattern, carbon sequestration and build-up of contaminants in soil with amendments application, though are slow process, but could be evaluated in oilseed cropping sequence. Influence of biosolids, animal manures, industrial waste etc. effect on oil quality can be tested to determine the impact of soil amendments. Biochar amendment is added to many field crops, but its application on oilseed crop is less studied. Studies on impact of biochar amendment on oilseed crop will improve understanding on carbon sequestration and oilseed quality. Exploring the possibility of converting woody CR like cotton, castor, pigeonpea stalks etc. into biochar amendments for soil carbon management. Biofertilizers or microbial inoculants for improving composting process of CR and its impact on oilseed crops is lacking. Most of the studies in oilseed are associated with rhizobial strains in soybean and groundnut crops. Limited studies are reported on the use of phosphate solubilizing microbes, sulfur oxidizing organisms, micro-nutrient activating microbes etc. in oilseed crop production of semi-arid regions. Studies on the effect of soil amendments on oilseed crops such as safflower, seasame are lacking. More research is needed to enhance nutrient content in composts and accelerate process of composting using suitable microbial consortia. More research is needed to transfer the advanced scientific knowledge for composting, enriching with micro-nutrients, use of different strains of microbes, reducing nutrient loss with additives should be promoted. Sound approaches to educate and create awareness among farmers about the benefits of various soil amendments in improving soil health, rather than supplying nutrients.

8. Conclusion

Soil amendments could bring paradigm shift in oilseed production, by including as suitable strategies for maximizing crop productivity and optimize environmental sustainability. Poor soil fertility, salinity, sodicity, low soil organic matter, reduced bioavailability of sulfur and micronutrients etc. are some major constrain in oilseed production. Therefore, inclusion of soil amendments in management practices will improve soil productivity and crop yield. Organic manures, compost, biosolids, biochar, biofertilizers etc. are few organic amendments. Inorganic amendments such as gypsum, pyrite, lime, zeolite etc. are few inorganic amendments which are used for enhancing oilseed production. Soil organic amendments will supply both nutrients and organic matter providing more opportunities to enhance soil physical, chemical and biological properties. Inclusion of amendments such as carbon stable amendments like biochar, can improve soil properties and act as carbon reserve for longer time. Biofertilizers are the potential organic amendments that would improve nutrient cycling, enhance soil biodiversity, producing siderophores, organic acids, chelateswould enhance essential nutrient accumulation in crops. The positive impact of soil amendments depends upon their composition, types of materials, soil type, utilization, weather conditions, cropping system etc. However, soil amendments are valuable asset that meets the present circular economy paradigm approach. Comprehensive analysis of organic and inorganic soil amendments should be performed prior to application in oilseed crops, to determine the potential and limitations with respect to soil health and crop quality. Locally available soil amendments such as organic manures, compost, green manure, CR, biofertilizers etc. should be utilized for soil and crop productivity. Use of organic amendments can be a low input system which could help in achieving sustainability of agroecosystem. Soil amendments have the potential positive impact on various ecosystem services depending upon their composition, stability, origin, application rate and utilization, soil type, cropping sequence, weather parameters etc. Hence, comprehensive characterization or soil amendments in relation to different agroecosystem must be carried out before soil application, so as to identify the potentials and limitation of give soil amendments on soil health and crop quality.

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Chapter 5

Nature of Importance of Various Parameters for Ideal Biofuel Crops: Special Reference to Rapeseed Mustard

Vanya Bawa and Sunil Kumar Rai

Abstract

To increase the performance of diesel engine and environment, the utilization of biofuel as a major source of renewable energy is justified. It is well understood that agri-based biofuel is always also the choice in case of utilization as biofuel because of requirement of processing and threat to food security. Therefore, scope of improvement increases as it is yet to efficiently exploit as major full in the world. There are numerous factors that influence the efficiency of a fuel and its combustion. The physiochemical properties, namely viscosity, surface tension, flash point, latent heat of vaporization, oxidation, etc., allow the fuel to work efficiently during combustion. Thus, interests in biofuels have been increased, and various experimental studies have been developed for diesel engines consisting of methanol and methyl ester of rapeseed oil. In a relevant study, to achieve ideal biofuel, various biotechnological advances at the frontiers of plant science to dissect the underlying traits for identification of fatty acid profile useful for oil production and quality are essential, thereby ensuring food security. The plant-based fuel and its efficient utilization depend upon its oil quality and quantity, which thereby can be evaluated and enhanced by various conventional and nonconventional approaches of engineering and plant sciences.

Keywords: biofuel, combustion, fatty acid profile, physiochemical, biotechnological

1. Introduction

The development of efficient fuel and its sustainability is the major topic of concern in the time of climate change and food insecurity. The generation of efficient sources of fuel and fiber delineates the ways for the development of sustainable sources of fuel. Biodiesel is an alternative to petroleum-based fuels derived from a variety of feedstocks; including vegetable oils, animal fats, and waste cooking oil [1]. At present, biodiesel is mainly produced from conventionally grown edible oils such as soybean, rapeseed, sunflower, and palm. The cost of biodiesel is the main obstacle to commercialization of the product [2, 3]. Biodiesel produced from edible oils is currently not economically feasible. On the other hand, extensive use of edible oils for biodiesel production may lead to food crisis. The complexity is diverse in case of food and fuel crops, and raw material is derived from plant seed oils and animal fats and is a mixture of the alkyl esters of long-chain fatty acids, mainly produced by trans-esterification methodology [4]. The concentration of useful fatty acid is the basis of selection, and the utility of biodiesel can be increased by focusing on the traits related to direct production of oil and its quality.

Before focusing on the mitigation practices, other ways of dissection of traits can be done to improvise the genetic architecture of crop plants. The dissection of various properties relevant to biofuel development can be targeted. The physicochemical properties of biodiesel are very similar to those of petroleum diesel and, therefore, could be used as an alternative to diesel in conventional diesel engines without the need for any modifications [5]. In contrast to conventional fuels, other advantages of biodiesel include higher cetane number, flash point, and lubricity, absence of sulfur, and lower aromatics content compared with the petroleum diesel [6, 7]. The density, viscosity, cetane number, linolenic acid, methyl ester, polyunsaturated methyl esters, acid value, glycerides content come under the major parameters of physiochemical properties and are considered before making suitable mixture with commercial diesel [8, 9]. These parameters are of prime importance to study before subjecting oilseed crops to get biofuel. The quality and content of oil are also of basic and utmost important feature to observe and determination for fatty acid profile and important physiochemical properties [10]. Currently, the majority of the commercial production of biodiesel is dependent on oils derived from palm, soybean, and rapeseed by conventional methods. Changing the direction of biodiesel production from food crops to nonedible plants requires significant improvements in oil yield and quality of these plants as well as in their tolerance to biotic and abiotic stresses. As discussed throughout the present article, biotechnological interventions and genetic engineering approaches have shown great potentials to achieve these goals [11]. However, the application of such technologies in oil plants is at their starting points, and there is no commercial oil plant with enhanced oil content or composition yet; there are laboratory and pilot-scale samples though. Moreover, it is also necessary to thoroughly evaluate the potentials of genetic engineering technology in improving several other attributes of oil plants, i.e., environment adaptation, production cost, and economic feasibility in field scale [12]. Lack of the presence of superior genotypes as a base for genetic engineering especially for nonedible plants such as *Jatropha,* which is known as one of the most important to study but not implemented and proved as one of the drawbacks in pursuing this path [13]. Developing high-throughput tissue culture and transformation protocols for oil plants is also very important to produce a large number of primary GM lines. This is very critical for especially woody perennial trees. Most of the GM oil crops have been evaluated at laboratory or greenhouse levels, and it is not clear that their responses under field conditions are yet to be looked into [14]. It should be noted that genetic engineering methods might sometimes seem technically successful but would lead to commercial failures at large-scale production [15]. Identification and characterization of major genes involved in TAG biosynthesis pathway as well as in adaptation to biotic and abiotic stresses are also of grave importance [16]. In addition, it is necessary to carry out gene pyramiding programs to collect different agronomical traits in single superior genotypes of oil plants. This would help breeders to accelerate achieving superior genotypes suitable for commercial biodiesel production. Another challenge would be the biosafety issues related to GM oil plants, necessitating performing environmental and health risk assessments for such plants before commercial release.

This would include evaluation of GM plants risks related to gene flow and potential negative effects on non-target organisms as well as the risks of potential negative effects on human and animal health.

2. Insight to physiochemical traits

The engine manufacturers are primarily focused on the efficiency of utilization of fuel. But while efficient biofuel is one priority area of research, the development of biofuel-efficient engines is another. Understanding the characteristics of biofuel leads to a vast field of study based on utilization, engine requirements, and efficiency. The criteria used to identify modifications in biofuel properties that either directly or indirectly affect fuel atomization and combustion define the biofuel's quality [17]. Key properties of efficient biofuel are its well to mix nature with air and ability to combust. The volatile nature of fuel is the major aspect of physical property. The volatile nature determines the Reid Vapor Pressure (RVP), measure of propensity of fuel. The ability of SI engine to startup when cold is another important requirement, at that time fuel vaporization signifies the utility and efficiency, as it determines the ease at which engine will start and blending percentage for good ignition. In the context of biofuels, ethanol has more latent heat of vaporization than gasoline fuel, requires more heat to get vaporized [18]. The higher electrical conductivity of biofuels restricts its 100% usage; hence, blending for good ignition is required, which opens up the scope of improvement in terms of ignition properties.

Commercial incorporation of biofuels as a major fuel is still critically overlooked as in case of diesel engines, fuel atomization process is having little time in combustion chamber when fuel is injected; the crucial step is determined by its important physical properties, namely fuel density, viscosity, fuel surface tension, and obviously the quality of biofuel occupies the position and creates huge scope of processing. The quality of the fatty acid profiles of biofuel or biodiesel fuels, with biodiesel having all higher values, significantly influences these physical properties. A sensor in the exhaust of modern engines can also detect changes in mixture, whereas biofuels with higher blends require more engine modifications. The chemical properties of biofuels are strongly affected by their different molecular structures; presence of oxygen is one of them. Whereas, resistance to self-ignition determines its higher octane number, shows it has resistance to knock [19].

The chemical properties of biofuel mixture are simply the sum of chemistries of each of the constituents, When consideration is taken in the context of modeling of biofuels in terms of molecular weight, the example can be used as methyl-butanoate, the approaches can be envisioned for answering the question of whether utilizing methyl-butanoate a model to study the kinetics of qualitative characteristics of long-chain fatty acids combustion. May be this can be used as a prerequisite to address the issues in modeling of ideal biofuel in order to mitigate the negative temperature coefficient behavior that causes ignition delay of biofuels [20]. The oxidative stability of biofuel is another important concern, with reference to canola/rapeseed derived biofuels, which contain unsaturated components in the oil. Presence of small amount of unsaturated fatty acids creates instability and is prone to photo oxidation, etc. [21]; hence, additives for oxidation stability are preferred in plant-derived fuels. Likely the concern is lowered when looking forward toward the oxygenated diesel fuels rather than the conventional ones; the presence of oxygen in biofuels is helpful in reducing the harmful emissions. Therefore, the oxidation of every individual part is critical in

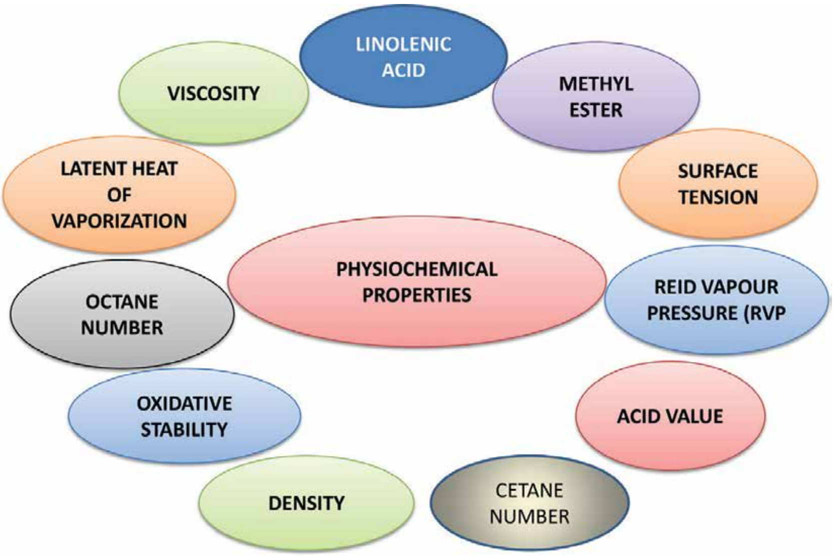

Figure 1.
Physiochemical parameters/factors affecting quality of biofuel.

the context of influencing the oxidation of other components, this result in the scope of determination of detailed chemical and kinetics study. The all physiochemical factors occupy the equivalent position when it comes to the production of efficient biofuel; the summary is shown in **Figure 1.**

3. Demand and area to address

The extent of biofuel production and its testing at various levels has increased in past few years as countries of the world are achieving in higher share in context of "green energy." The world is going toward sustainable options to minimize the global pollution and energy scarcity problem. The need of proper manipulation and effective utilization is required to for achievement of self-sufficiency, thereby working under national and international policies. To expedite the process of identification of diversity in fuels and the pattern in demand based upon quality of biofuel can describe the greater way to exploit specified crop plants for fulfilling global energy demands. The pattern of various results showed that consumption of plant-derived fuel has been increased since 2000 [22].

The history suggests that initially production of first generation biofuels was from agricultural raw material. The renewable source of biofuels includes vegetable oil, which is utilized for its production by transesterification method. Whereas the major input material for biodiesel production in EU is rapeseed mustard oil and accounts for 57–70% of biodiesel production [22]. The utilization of plant-based fuel brings the idea of HEAR oil and to utilize it as biodiesel for its characteristic properties with high number of carbon atoms (C22:1) and potentially to produce good amount of energy [23]. Studies reported that rapeseed mustard utilization for biofuel production has become more independent and is gradually converting into significant in terms of industrial use [24], claiming as per EU biofuel directive (2003/30/EC) implemented targets for biofuel. The total biofuel product using rapeseed as primary input for biofuel production for industrial purpose shares total production until 15–40%., whereas the rest of the produce was utilized as primary purpose, which includes food feed and postharvest processing. Zentková and Cvengrošová (2013) reported that the ever-increasing demand of biodiesel leads to an increase in production and acreage of rapeseed as an input for biodiesel production. This need to render the demands of global fuel can open the significant opportunities for farmers and allied sectors, the placement of their production to mitigate the farmers paradox of too high production and low demand. The production followed by better utilization will accelerate the biodiesel production via identified efficient methods.

It is to be noted that global food demand will change with the bifurcation of utilization of rapeseed mustard especially for the countries where it is major edible oil seed crop. Hence, methods to develop quality fatty acid profile with special reference to biodiesel production will develop the case of its production and consumption security. To achieve this by balancing the food demand and oil production for fuel manipulation and efficient usage of conventional and nonconventional approaches are required. However, to offer the better choice of healthy and acceptable food to the consumer a coordination of plant breeding, food processing and nutrition science is required, which can exponentially increase the specific traits in relation to oil quality suitable for biodiesel without altering the yield.

The focused quality production by rendering the modification of fatty acid composition of rapeseed oil is required and recommended. The production of rapeseed lines with good amount of lauric acid and myrestic acid identifies the one quality toward energy source. To address the check points in case of quality parameters plant pathways and various linked genes can be identified and triggered leading to the efficient carbon fixation and its conversion to lipids. Therefore, identification and understanding lipid biosynthesis pathways can delineate the ways to induce the relevant system in development of mutation breeding programs in plant breeding for the development of long-chain fatty acid rapeseed genotypes beyond current level [23, 25].

During the last decades, different plant breeding strategies have been used to improve oil yield and quality, and work has been done to improve tolerance in terms of biotic and abiotic stresses in edible and nonedible oil plants. New biotechnological tools such as marker-aided selection, next-generation sequencing, "omics" technologies, and genetic engineering have accelerated the breeding process for such traits in these kinds of plants. Identification and isolation of major genes involved in the lipid biosynthesis pathways using omics technologies and their transfer to edible and nonedible oil plants are expected to result in economical oil production in such plants as feedstock for biodiesel production [26]. Different genetic engineering strategies aimed at changing the structure of the enzymes as well as overexpression or silencing of the genes involved in the oil production pathway have been used to enhance oil yield and quality in nonedible oil plants. In this article, recent advances in the field of plant genetic engineering for improving oil production in biofuel crops and in particular in tow of the most promising nonedible plants, i.e., *Jatropha* and *Camelina* are reviewed and discussed [27].

4. Conventional strategies to enhance oil production in biofuel crops

To achieve commercial biodiesel production from nonedible oil plants, development of new varieties/hybrids of oil plants with high oil contents, tolerance to biotic and abiotic stresses, and no toxic proteins are a critical step. During the last decade, different breeding strategies have been used to improve these traits in crop plants of interest. The main activities pursued in plant breeding include developing variation, selection, evaluation for target traits, multiplication, and finally, release and distribution of new varieties [28]. Commonly, creation of genetic variation is performed through domestication, germplasm collection, introduction, intra- and inter-species hybridization, mutation, polyploidy, somaclonal variation, germaclonal variation, and genetic engineering [29, 30]. During the last decades, using conventional breeding strategies, different edible and nonedible oil plants have been improved to enhance oil quality, oil yield, and tolerance to biotic and abiotic stresses [31, 32]. In spite of such successful experiences, these methods face some disadvantages, such as being laborious and time-consuming, low accuracy in achieving desired traits, impossibility of inter-species hybridizations and wild crosses. The long methodologies and less precision created gap between identification of lines with potential to be the source of biofuels and the application for production of biodiesel.

5. Nonconventional tools and techniques

Recent advances in next-generation sequencing technologies (NGS) have encouraged rapid development of bioenergy crops. Different new "omics" technologies (genomics, transcriptomics, metabolomics, and metagenomics), marker-aided selection (MAS), and genetic engineering approaches have been considered and are widely used as the most promising solutions to improve agronomic traits in bioenergy oil plants. "Omics" technologies can accelerate and be used for the identification of novel and useful genes responsible for oil production, to discover oil production pathways including mapping of significant QTLs in the family [33] and also to improve oil content and composition [34]. The tremendous efforts in terms of genome analysis have been done in Crucifereae family [35]. To facilitate such efforts, whole genomes of some oil plants including soybean [36], rapeseed [37] sunflower [38], castor [39], Jatropha [40], oil palm [41, 42], Camelina [43] have been already sequenced. Such huge deal of data has opened a new high-throughput way to discover

Germplasm	Marker system	QTL identified	References
520	60 K SNP array		[44]
177	Sequence by genotyping	12	[45]
370	60 K SNP arrays	11	[46]
	37,721 filtered SNPs	37SNP	[46]
300 inbred lines	201,817 SNPs (SLAF sequencing by an Illumina HiseqTM 2500)	30 SNP	[47]
RILs(GH06 X P174)		40 QTLs	[48]
segregation population BC_1F_1	251 markers of RAPD, SSR, and SRAP.	19 QTLs	[49]
94 $F_{7\text{–}8}$ recombinant inbred lines (RILs)	143 (SRAPs) and 38 (SSRs)	4QTLs	[50]
DHs (Polo × Topas)		131 QTL	[51]

Table 1.
Nonconventional/biotechnological efforts.

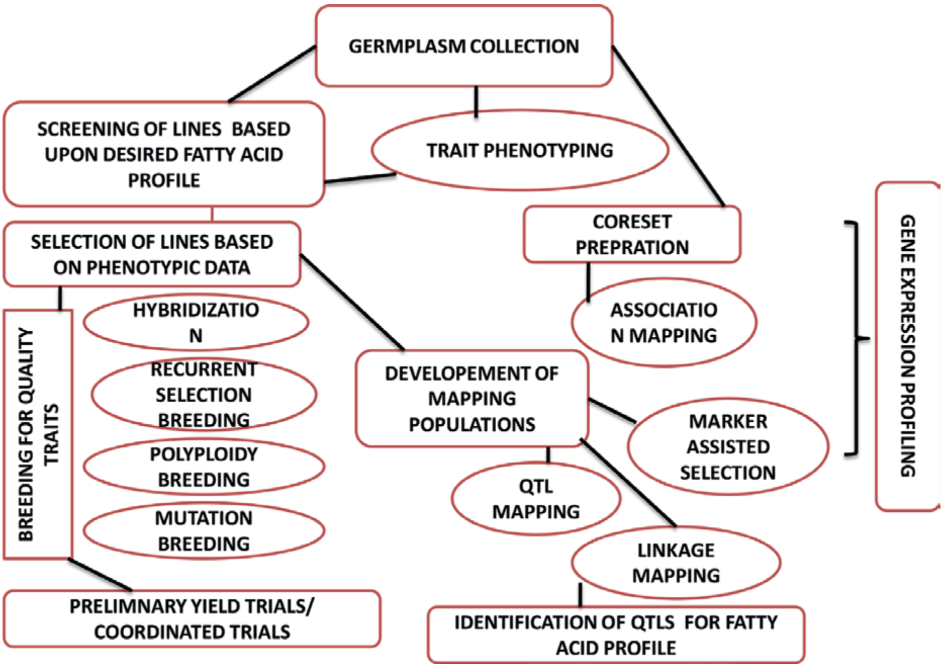

Figure 2.
Conventional and nonconventional approaches to improve fatty acid profile in oilseeds.

genes and pathways involved in oil production as well as the genes affecting oil quality in these plants. Moreover, by using omics technologies, such as quantitative trait locus (QTL) mapping, single-nucleotide polymorphism (SNP), and expressed sequence tag (EST)-based molecular markers, cDNA libraries, and RNA-seq analysis, researchers could identify and characterize genes involved in lipid synthesis pathways, tolerance to biotic and abiotic stresses, and the other important traits (Tang et al., 2017) [27], and similar few nonconventional efforts are summarized in **Table 1**.

This chapter creates the two paths that cross each other while selection and development of ideal biofuel crops in conventional and nonconventional ways. The strategies are not only based upon the extraction and utilization of oil but first going into the system of plants using genetic dissection methods that can delineate the mechanisms of gene responsible for the development of useful fatty acid profile. The triggers can be developed to identify useful genes, thereby understanding their expression profiling in **Figure 2**.

6. Conclusion

Utilization of biofuels has gained popularity as population is growing and need for the more diverse sources for fuel production. The plant-derived fuel still requires lot of efforts in terms of its modification to fit into the system of efficient utilization. The efficiency and usage can be increased by intensive study into the characteristic features of these plant-derived fuels with minimizing the threat to food security. The first aspect is to understand and evaluate the physiochemical nature taking petroleum based fuel as standard check. Other approach can be through understanding the mechanism of fatty acid formation and identification of potent gene sources to increase the fatty acid profile. Thereby molecular dissection is another suggested approach as it is believed to be successful in many crops. The omics technologies can accelerate the process to dissect the genetic features for required traits. Hence, comprehensive approach is required to mitigate the problem of underutilization of biofuels. The barrier can be reduced by focusing on evaluation of all properties of the oil and its maximum efficiency.

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Chapter 6

Macauba (*Acrocomia aculeata*): Biology, Oil Processing, and Technological Potential

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Abstract

The global production of vegetable oil has increased since the beginning of the century, reaching a peak of 209 million tons in 2020/2021 and is projected to continue to increase due to population growth and the impact of the biodiesel industry. In this context, palm oil and soybean oil have stood out. However, both palm oil and soybean oil production chains are not fully sustainable, leading to socioeconomic and environmental challenges, which have driven the search for new raw materials with sustainability potential. Macauba [*Acrocomia aculeata* (Jacq.) Lodd. Ex Mart.] is an oleaginous palm distributed mainly in Central and South America, and most of the Brazilian territory. It is one of the species with greater potential for economic exploitation due to its high oil productivity and use of by-products from oil extraction and processing. This chapter addresses the most up-to-date information in biology, oil production, and oil processing from fruit to oil applications.

Keywords: *A. aculeata*, macauba, oil extraction, oil refining, biofuel

1. Introduction

The world population growth brings great challenges regarding food security and environmental sustainability [1]. In this scenario, increasing the production of vegetable oils by developing resilient and sustainable cropping systems may be a promising approach. The global production of vegetable oil is dependent on the production of tropical perennial oilseed plants, in particular the African palm (*Elaeis guineensis*) [2]. In 2019–2020, over 81.1 Mt of *E. guineensis* oil was produced worldwide, of which 72.3 Mt consisted of palm oil (mesocarp), and 8.8 Mt. of kernel oil (endocarp) [3]. However, the cultivation of this species requires specific soil and climate conditions, leading to the deforestation of large areas of the rainforests, with considerable environmental impact and competition for land intended for food cultivation [4].

In this context, the identification of oilseed plant species that contain oils with triacylglycerol composition similar to palm oil, high production yield, and greater resistance to adverse edaphoclimatic conditions is a challenge. Macauba [*Acrocomia aculeata* (Jacq.) Lodd. Ex Mart.] is an endemic palm species of the Americas that presents all these peculiarities, becoming a promising alternative for the development of a sustainable production chain of oils and co-products of industrial interest [5–7].

A. aculeata is popularly known as macauba, macaíba, macaiuva, mocaja, mocuja, mucaja, bacaiuva, bocaiuva, coco-de-catarro, coco-de-espinho, imbocaia, and umbocaiuva, depending on the region of occurrence [8]. Analyses of the productive capacity of macauba crops in Brazil indicate that approximately 5000 kg of pulp oil and 1500 kg of kernel oil can be produced per hectare per year. In addition, macauba is considered the second-largest oleaginous source after palm oil concerning the production yield [5, 9, 10].

This plant species grows preferably in tropical and subtropical regions with high rainfall and solar irradiation [11]. However, it is able to adapt well to other environments, including subtropical and semiarid conditions [9]. In Brazil, there is a large quantity of degraded land or land in process of degradation or desertification caused by human action or natural phenomena. Land degradation is the loss of productivity due to factors such as soil erosion, reduction of soil fertility, and loss of natural vegetation [12]. The fact that macauba has a great capacity to adapt to extreme edaphoclimatic conditions has led to the proposal that this plant could contribute to the recovery of degraded lands [13].

The energy capacity of macauba is due to the high productivity and quality of the pulp and kernel oils. Macauba oils have a different fatty acid profile and minority compounds. The pulp oil has a predominance of unsaturated fatty acids and bioactive compounds, such as carotenoids and tocopherols [14]. In turn, kernel oil is rich in saturated fatty acids, mainly lauric acid. These notable differences confer distinct market potential for both products [15].

In the last decade, studies on *A. aculeata* have intensified due to its characteristics and applications, mainly as an alternative feedstock for biodiesel production [16]. Soybean oil, canola oil, rapeseed oil, cottonseed oil, and palm oil are examples of noble and edible feedstocks used for biodiesel production [17]. In 2020, soybean oil accounted for 71.4% of biodiesel production in Brazil [18]. Studies have shown a similar profile of fatty acid esters in biodiesel from macauba oil when compared to soybean oil [19], highlighting the fundamental role of macauba as a potential feedstock with high availability and productivity for use in the biodiesel industry [5].

Due to the essentially extractive nature of macauba cultivation, in many cases, good practices for harvesting and storing the raw material are not followed, and this directly impacts the quality of the fruits and oils obtained [10]. In Brazil, there are several commercial cultivation programs demonstrating that it is a viable strategy, although it is still far from competing with commodities. The processing of macauba oils begins with the process of extraction by continuous pressing to obtain the crude oil [20]. Subsequently, the oils must undergo a refining process in order to eliminate undesirable substances that compromise both the oxidative stability of these oils and their organoleptic qualities [20]. Once refined, oils can have several applications both in the food and oleochemical areas and can still undergo modifications to expand their range of applications [15]. **Figure 1** outlines the complete macauba oil production chain from the palm tree to the lipid modified.

Excellent studies on the biology of macauba have been reported, including the factors that influence productivity, domestication processes, and genetic improvement, aiming for the development of commercial crops, and genetic variability, among others. Recently, Vargas-Carpinteiro et al. have published an exhaustive review on *Acrocomia*, showing that studies on harvesting, postharvest, crude oil extraction, refining, and deodorization are among the most incipient topics [7]. Therefore, the

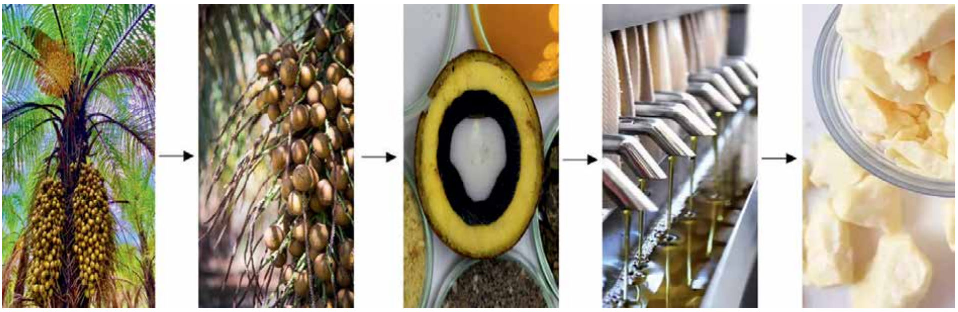

Figure 1.
Representation of the macauba oil production chain: Palm, fruit bunches, open fruit, processing of oils, and lipids modification (photos source: S. Oleum).

present study addresses the biology of *A. aculeata*, with emphasis on the processing steps from fruit to oil, as well as the main applications of macauba oils.

2. Biology

2.1 Taxonomic classification and distribution

Macauba is a palm species that belongs to the Arecaceae family, which includes approximately 189 genera and about 3000 species, which are classified into five subfamilies, as follows: Calamoideae, Nypoideae, Coryphoideae, Ceroxyloideae, and Arecoideae [21]. The latter is the most representative family since it contains species of great economic interest such as *Elaeis guineensis* (African palm), *Cocos nucifera*, *Euterpe oleracea,* and the emerging species *Acrocomia aculeata* (macauba) [21]. The great phenotypic diversity among individuals of *A. aculeata* (Jacq.) Lodd. ex-Mart has led to a misunderstanding about the number of species that belong to the genus *Acrocomia*. For this reason, there is still no consensus on the taxonomy of this genus [22]. Recent studies using both morphoanatomical characteristics of the plant and fruit biometrics have contributed to the understanding of the taxonomy of this group [23–27].

Currently, nine species are included within the genus *Acrocomia* that occur in the Neotropical region, including *A. aculeata*, *A. crispa*, *A. emensis*, *A. corumbaensis*, *A. glaucescens*, *A. hassleri*, *A. intumescens*, *A. media*, and *A. totai* [22]. Fossil studies and the great phenotypic diversity of the genus *Acrocomia* suggest that Brazil may be the center of origin and dispersal of these species [28], probably due to both weathering processes and human activity in the Americas [22]. The species *A. aculeata* is endemic to Brazil and has been distributed to islands in the Caribbean, Central America, and South America [22]. In Brazil, this palm occurs in most of the territory, mainly in the states of Minas Gerais, São Paulo, Goias, Mato Grosso, and Mato Grosso do Sul, in the Cerrado [22, 29]. It can also be found in tropical and subtropical forests, and dry forests of Caatinga [23, 30], with good adaptation to sandy soils and regions with low water availability [24].

2.2 Morphology and reproduction

Macauba is a perennial, halophytic, tree-like palm species with a solitary, aerial, cylindrical, and spindle-shaped stem that can reach 10–15 m in height and 20–30 cm in diameter. The stipe is often covered by the bases of the petioles, which remain attached for many years. The node region is covered with dark and sharp spines and is approximately 10 cm long [31].

The *A. aculeata* genome has 2.8 Gbp distributed on 15 pairs of chromosomes (2n = 30) with an AT base content of 58.3% [32]. This palm is monoecious and presents interfoliate and branched spadix-like yellow inflorescences 50–80 cm long. It presents a large number of staminate flowers at the base and pistillate flowers originate triad at the top of the inflorescence [30, 33]. Although the reproductive system is cross-pollination between different individuals, the species is self-compatible [33]. Entomophily is the main pollination route, and anemophily plays a secondary role. Scariot et al. suggested that the combination of these two types of pollination with a flexible reproductive system is related to the wide distribution of the species [33].

Macauba flowering is seasonal and annual. In Brazil, it blooms from September to February, with peak flowering in November and December [33]. However, fruiting occurs throughout the year and the fruits mature approximately 1 year after fertilization [33]. Macauba generates inflorescences with bulky clusters that contain 300–600 drupaceous fruits, weighing about 66 g/each, resulting in a highly productive plant [13].

The fruits can be 3.0–5.0 cm in diameter, are edible, spherical, and do not ferment immediately after ripening [5]. The fruit contains approximately 20% epicarp (peel), 40% mesocarp (pulp), 33% endocarp, and 7% kernel [34]. The epicarp ruptures easily when ripe. The mesocarp is fibrous, mucilaginous, sweet-tasting, edible, and rich in glycerides, yellow or whitish in color. The endocarp is strongly adhered to the pulp, with a black bony wall, and an edible oily kernel covered by a thin layer of the tegument. Each fruit usually contains a seed surrounded by a hard, dark endocarp approximately 3-mm thick [30, 35]. Macauba has two economically important kinds of oil, stored in the fruit pulp and its kernel. The pulp contains up to 75% of the total lipids, while the kernel may contain up to 65%, both on a dry basis [34]. **Table 1** shows the proximate composition of *A. aculeata* pulp and kernel.

2.3 Domestication and plant breeding

Macauba, like most palm species, has an essentially extractive cultivation system, leading to habitat fragmentation, increasing inbreeding, and decreasing genetic diversity [37]. Both the domestication process and the development of breeding programs for *A. aculeata* are still at an incipient stage [27, 38]. However, its domestication

	Kernel %	Pulp %
Dry matter	83.11	42.65
Ash	1.29	2.03
Crude protein	5.66	1.15
Lipids	47.76	32.05
Crude fiber	62.79	51.70
Mineral matter	0.39	0.66
Carbohydrates	33.40	18.10
Moisture	3.18	45.42

Table 1.
Proximate composition of macauba fruit. Source: Lira et al. [36].

should be integral and systematic due to the socioeconomic impact of the cultivation of this palm and the application prospects [7]. The success of the domestication process depends on genetic improvement programs that are directly related to the choice of genotypes with the best agronomic characteristics [39]. Knowledge about the genetic diversity of *A. aculeata* is fundamental to guiding the selection of the most promising materials for use in the crop, maximizing genetic gains, and contributing to the creation of commercial cultivars [38]. Colombo et al. pointed out the main guidelines for the improvement of *Acrocomia* plants, including obtaining varieties with optimized height, greater drought tolerance, and higher oil productivity [5].

There is great morphometric and genetic variability among macauba plants native to the Brazilian Cerrado and Pantanal regions of Brazil and Costa Rica, characterized by fruit biometry and oil yield [34, 40, 41]. However, these factors are not correlated [40]. Biometric studies of Costa Rican varieties have suggested a possible environmental effect on oil composition and yield [41]. Dos Santos et al. [42] studied the accumulation of metabolites in fruits coming from three Brazilian regions (Southeast, Northeast, and Midwest) characterized by having different lipid contents. The authors concluded that, despite the anatomical differences between mesocarp and endocarp, in both tissues, a similar trend of metabolite accumulation was observed toward ripening. In the mesocarp, total soluble proteins, free amino acids, sucrose, starch, and total lipids accumulate toward maturity, with a decrease in glucose and fructose contents. The endosperm differed from the mesocarp only for the amino acid contents, which decreased in mature fruits. The results pointed out that fruits from the Southeast region (Minas Gerais) may be of interest for breeding studies due to their higher lipid contents [42].

Genomics-based strategies allow access to the genetic potential of natural populations, germplasm characterization, phylogenetic analysis, etc. [38]. The availability of public databases (www.ncbi.nhi.gov) of genomic sequences of *A. aculeata* has enabled great advances in genetic variability studies in the last decade. Those studies confirm the high genetic diversity among varieties, allowing the identification of genotypes with the highest agronomic potential, the abiotic factors related to increased oil production, and the efficiency of biosynthesis, evolution, and phylogeny of this species [32, 40, 43–45].

The embryo culture of *A. aculeata* allows the achievement of high germination rates, solving the deep seed dormancy that causes low germination rates [46]. However, the acclimation process restricts seedling growth. Recent histological studies have pointed to impaired development of the haustoria, root system, and leaves as the possible causes of this phenomenon [18]. Souza et al. [47] evaluated the effects of climate seasonality on the longevity and dormancy of diaspores of macauba palm. That approach is critical for establishing soil seed banks that allow for the conservation of natural populations and extractive management. The authors reported that the longevity of macauba seeds in the soil depends on several factors, including the maintenance of structural protection of the embryo, tolerance to water deficits, and control of oxidative stress. In turn, the overcoming of dormancy is related to the gradual weakening of the containment tissues and the strength of the embryo [47].

In this context, the development of genetic improvement programs for macauba to allow systematic cultivation and commercialization on a large scale in the near future is required. Initiatives to cultivate macauba in Brazil for commercial purposes have been undertaken, including the programs Entaban Brazil, Solea, and Inocas, with production destined for national consumption [5].

3. From macauba fruit to refined oil: modifications

3.1 Fruit processing

The harvest and storage stages of fruits are determinants of the quality of agricultural products. Both the harvest method and the development stage of macauba fruit at the time of harvest directly impact the quality of the oil [16]. The storage time of the fruits before the oil extraction also has a great impact on the product quality, which is determinant in humid tropical countries [37]. In the extractive cultivation system of macauba, the fruits are collected directly from the soil, after the natural fall at the end of the fruiting period, and stored with no controlled humidity and temperature conditions, resulting in low-quality oils and yield [16].

Data have shown an increase in oil content at the end of the maturation period of macauba fruits, thus harvesting bunches at the end of this phase is recommended. However, the proportions of fatty acids and triacylglycerols of both pulp and kernel oils do not vary [48]. A very important peculiarity of the macauba fruit is the additional oil synthesis after abscission, which differentiates it from other palm species, including *E. guineensis*. Studies have shown that such production can reach up to 35% after 40 days of storage under ambient conditions [16]. Therefore, the harvest and postharvest stages of macauba fruits are crucial in the productivity and quality of crude oil, mainly concerning the acidity index and oxidative stability.

The acidity index is a measure of the free fatty acids content in the oil. Oils with acidity levels >5% expressed as free fatty acids compromise the later stages of processing and commercialization [49]. The increase in free fatty acids in the oil from the mesocarp is due to the action of lipases (E.C. 3.1.1.3; glycerol ester hydrolases) that hydrolyze triacylglycerols in the presence of water. These enzymes are produced by plants, animals, and microorganisms [50], and the latter are recognized as potential producers of extracellular lipases [51]. Cavalcanti-Oliveira et al. analyzed the origin of lipases involved in the hydrolysis of macauba pulp oil [52]. The results suggested that the oil from the mesocarp is hydrolyzed by lipases produced by microorganisms that contaminate the fruit when in contact with soil, rather than the action of endogenous lipases. Some authors have reported that macauba fruits harvested directly from the bunch or naturally fallen fruits with no contact with the soil can be stored under ambient conditions for up to 20 days, without exceeding 5% acidity [16, 18, 53]. However, a varied microbiota can be found in the epicarp and mesocarp of macauba fruits without contact with the soil [16].

Thus, efficient harvesting methods and rapid fruit processing are required to slow pulp decomposition and oil acidification [54]. Fresh macauba fruit has high-quality mesocarp oil, even when it is dried immediately after harvest, provided that good harvesting and processing practices are applied [55]. Drying the fruit after harvest decreases the moisture content and reduces the hydrolysis efficiency of lipases in addition to facilitating pulping with simultaneous separation of the peel [56]. The combination of drying and autoclaving processes of macauba fruits allowed the storage of crude oil for 180 days, preserving the original acidity and the triacylglycerol profile [52]. It is worth noting that under good harvesting and storage practices, the acidification process of macauba pulp oil is slower than palm oil [55]. Other methods of treating the fruit immediately after harvest have been used to extend the shelf life of the fruit and the oil quality, including the use of ozone gas, irradiation, and different drying methods [53, 57, 58].

Evaristo et al. [16] reported a significant increase in the oil content of the mesocarp after the fruits were detached from the bunch, suggesting that macauba has climacteric behavior. The authors showed that harvesting macauba fruit directly from the bunch and the immediate storage under controlled humidity and temperature conditions, as well as the treatment with fungicides, resulted in higher fruit quality and therefore longer postharvest shelf life [16].

Improvements in fruit processing steps that positively impact the quantity and quality of the extracted oil can increase productivity and make the macauba more commercially competitive [56].

3.2 Obtaining crude oil

Three important steps should be considered for obtaining the crude oil, which directly affects the oil quality and product yield, including the storage of the raw material, preparation, and extraction of the crude oil. The variation in moisture content and temperature during fruit storage can trigger enzymatic and oxidation reactions, leading to a reduction in the quality of the oil extracted due to the increase in free fatty acids and other degradation compounds, known as peroxides [20].

The proximate composition of the macauba fruit consists of 47.76% and 32.05% lipids in the kernel and pulp, respectively; thus, continuous pressing is the most suitable method for oil extraction due to the high lipid contents [36, 59].

The screw-type press, also known as screw expeller, is a continuous press in which the fruit pulp or kernel is fed into a thick-walled cylinder containing a rotating, polished screw with gradually decreasing size. The oil from the plant cell is in the form of globules covered by a cell membrane. A typical characteristic of plant cells is the presence of thick cell walls; thus, the cell wall should be broken down to get the oil globules out. For that, the pulp or kernel cluster is fed continuously into the press and compressed at high pressure (4–35 MPa). In turn, while the oil is extracted, the compressed fruit cake is discarded at the end of the stretch. The high-energy consumption generated during shearing can considerably increase the temperature of both the oil and cake [20].

3.3 Physicochemical characterization of macauba oils

3.3.1 Composition of saponifiable and unsaponifiable fractions

Chemically, oils and fats are mixtures composed mainly of triacylglycerols formed from a glycerol molecule esterified with three fatty acids. The crude oil usually contains monoacylglycerols, diacylglycerols, free fatty acids, waxes, phospholipids, sphingolipids, glycolipids, terpenes, sterols, tocopherols, and carotenoids as minority compounds [20]. The unsaponifiable matter consists of solubilized minority compounds in oils and fats that are extractable with organic solvents after saponification [60]. Nunes (2013) found 0.76% unsaponifiable matter in crude macauba pulp oil, while Breves (2018) found 2% unsaponifiable matter in crude macauba kernel oil [61, 62].

3.3.2 Fatty acid composition

The macauba kernel oil is characterized by the predominance of oleic acid and lauric acid, and presents a translucent aspect, while the pulp oil has an orange color and is characterized by a high concentration of oleic acid and carotenoids, which may

Fatty acids		**Pulp (%)**	**Kernel (%)**
C4:0	**Butyric**	**Traces**	**0.91**
C6:0	Caproic	0.22	0.27
C8:0	Caprylic	0.11	3.67
C10:0	Capric	Traces	2.79
C12:0	Lauric	0.39	32.58
C14:0	Myristic	0.38	9.71
C16:0	Palmitic	24.6	8.25
C16:1	Palmitoleic	4.27	—
C18:0	Stearic	1.08	2.24
C18:1	Oleic	52.57	36.27
C18:2	Linoleic	13.80	3.82
C18:3	Linolenic	2.26	—
C20:0	Arachidic	Traces	—
C22:0	Behenic	Traces	—
C24:0	Lignoceric	0.32	—
Σ saturated	—	27.10	59.92
Σ unsaturated	—	72.90	40.09

Table 2.
Fatty acid profile of macauba oils (pulp and kernel). Source: Coimbra and Jorge [14].

provide high oxidative stability [63, 64]. **Table 2** presents the fatty acids profile of macauba pulp and kernel oils.

The low content of polyunsaturated fatty acids (linoleic—C18:2 and linolenic—C18:3) can also affect the oxidative stability of the pulp oil, corresponding to 15%. On the other hand, the kernel oil presents a peculiar fatty acid composition, because although it has 32.58% of lauric acid (C12:0), which is a lower level when compared to conventional lauric oils, such as coconut, palm kernel, and babassu, it has more than 35% of oleic acid, an unusual content among all vegetable oils of this class.

3.3.3 Triacylglycerol composition

The macauba pulp oil presents a smaller range of carbon groups, comprising 48–54 carbon groups. Fourteen distinct triacylglycerols were identified, corresponding to 17.07% OOO, 6.36% OOL, 28.53% POO, and 10.53% PLP [65]. Lieb et al. analyzed macauba pulp oil from Costa Rica and found 20.8% OOO, 10.4% OOL, 13.0% POO, and 1.5% PLP (P: palmitic; Po: palmitoleic, S: stearic; O: oleic; L: linoleic) [48]. This divergence of values is due to the different origins of the fruits and the extraction method used to obtain the crude oil.

3.3.4 Tocopherols, carotenoids, and phenolic compounds

Natural antioxidants found in vegetable oils, such as tocopherols and tocotrienols, have four isomers, designated as alpha (α), beta (β), gamma (γ), and delta (δ),

	Macauba pulp oil (mg kg $^{-1}$)	Macauba kernel oil (mg kg $^{-1}$)
Phenolic compounds	2.21	4.38
Total carotenoids	300.1	1.82
Total tocopherol	221.95	23.10
α-Tocopherol	143.70	14.35
β-Tocopherol	3.25	0.85
γ-Tocopherol	57.83	—
δ-Tocopherol	8.15	7.90

Source: Coimbra and Jorge [14].

Table 3.
Tocopherols, carotenoids, and phenolics concentrations in macauba oils.

depending on the number and position of methyl groups in a chromanol ring. Tocopherols are characterized by a saturated side chain, while tocotrienols present an unsaturated side chain, and they also have a vitamin E activity in humans. They are also recognized for slowing down the lipid oxidation process. The antioxidant activity of tocopherols in food increases progressively for the δ, β, γ, and α isomers. On the other hand, tocotrienols are less effective than their corresponding isomers [66].

Carotenoids constitute a diverse group of lipophilic compounds that provide yellowish to red color to oils and are also known as bioactive compounds with proven health benefits [66].

Coimbra and Jorge characterized the macauba kernel and pulp oils for the concentration of phenolic compounds, carotenoids, and tocopherols, and the findings are shown in **Table 3** [14].

3.3.5 Oxidative stability

Factors that affect or catalyze the lipid oxidation include the presence of unsaturated or double bonds in fatty acids, light, temperature, prooxidants and antioxidants, enzymes, and storage conditions. In addition, the oxidative stability reflects the quality of the raw material from harvest to processing, leading to undesirable flavors that reduce the quality and shelf life of oils [67].

Breves [62] studied the oxidative stability of macauba kernel and pulp oils according to ISO 6886, and reported 41.35 and 16.36 min at 110°C, respectively. It is worth noting that the stability of the pulp oil is relatively lower than that of the kernel oil, due to the higher number of unsaturated fatty acids [62].

3.3.6 Oil refining

Refining can be defined as a series of distinct steps aimed at reducing undesirable substances from crude oils that can affect the stability and sensory properties. It removes colloidal substances, phosphatides, free fatty acids, natural pigments, such as chlorophyll and carotenoids, inorganic substances, such as calcium salts, metals, and phosphates, among others, and volatile compounds, such as peroxides, hydrocarbons, alcohols, aldehydes, ketones, and low-molecular weight esters, and water [20].

The selection of the adequate refining process is directly related to the free fatty acid content (%) of the crude oil and can be done through a chemical or physical process.

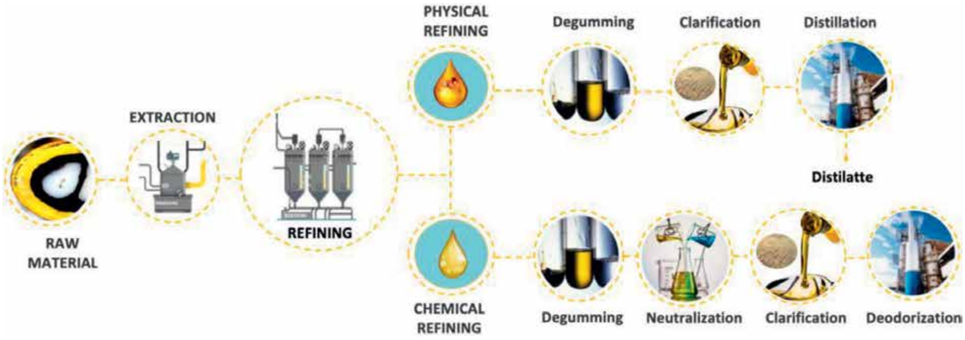

Figure 2.
Schematic diagram of the typical process for obtaining refined oil from the raw material of interest.

The chemical process is not indicated for high acidity oils since significant losses of neutral lipids may occur due to saponification or soapstock dragging. For acidic oils, physical refining is indicated and should be performed under high temperature and low pressure, volatilizing and removing free fatty acids with reduced loss of neutral lipids [68].

In addition, phospholipid contents are the second factor to be considered before selecting the refining process. Chemical refining is indicated for high phosphorus levels, while the physical refining process is more usual for oils with low phosphorus levels [60]. For macauba pulp oil, both types of refining can be used due to its non-standardization as acidic oil (**Figure 2**).

Degumming is the first step for obtaining the refined oil, either for physical or chemical processes, in which phospholipids are converted into oil-insoluble hydratable gums that are easily separated by sedimentation, filtration, or centrifugation through the addition of water and/or acid solution. This step is important for the removal of phospholipids, which can precipitate during the storage, affecting the quality of the oil and the subsequent refining steps. Additionally, it is possible to obtain lecithin, which is a by-product of high commercial value due to its emulsifying effect [20, 60].

Neutralization is carried out during the chemical refining and consists of neutralizing and thus reducing the free fatty acids content by adding an alkaline solution. Diluted caustic soda is usually used in concentrations between 10 and 24° Bé (degrees Baumé). The concentration of caustic soda and its excess is dependent on the free fatty acids (FFA) content of the degummed oil to be neutralized, avoiding saponification of the oil [69].

The next step is known as clarification or bleaching. Its main objective is to remove pigments to obtain clear oils (an important factor for commercialization), in addition to removing other constituents, such as oxidation products, metal traces, phospholipids, and soaps, resulting from the chemical refining. According to Kaynak et al. [70], these impurities, when present in the oil, can contaminate the hydrogenation and interesterification catalysts, darken the oil, and decrease oxidative stability [20, 70].

The efficiency of the process is determined by adding clarifying clays, either natural or activated, via adsorption. Part of the pigments is adsorbed onto the clarifying clay through surface attraction forces, known as "Van de Waals forces." Other components are chemically bound to the surface of the clarifying clays by covalent or ionic bonds. Part of the impurities present in the oil is removed by trapping their molecules in the pores of the clay. Some minor components, such as oxidation compounds and pigments, are chemically altered during clarification due to the catalytic activity of some clays [69].

Deodorization is the last step of chemical refining, with the elimination of volatile compounds such as remaining free fatty acids and peroxides that give the oil an unpleasant aroma and flavor. The deodorization is done through steam distillation, removing volatile substances through a high vacuum [69].

In physical refining, the last step consists of distillation, with oil deacidification through the removal of free fatty acids, volatiles, and oxidation products [69]. The process is carried out through the association of high temperature and low absolute pressure, favoring the acceleration of distillation and preserving the oil from atmospheric oxidation [61].

According to the CODEX Alimentarius CXS 210-199 for vegetable oils, refined oils should have a maximum acidity of 0.6 mg KOH/g oil and up to 10 mEq O_2 kg^{-1} [71].

3.3.7 Refining the by-product: deodorizing the distillate

It is estimated that a great amount of industrialized vegetable products, corresponding to 15–20%, are not used. The volume of these residues can reach even higher levels depending on the raw material, the processing applied, equipment used, and process yield, among others. All these factors induce the generation of by-products for food, fertilization, and feed production. Researchers have attempted to use by-products from the processing of vegetable raw materials, including vegetable oils, and once besides adding value to the by-products, it reduces the disposal in nature, helps in the environmental preservation, and promotes the integral use of the vegetable sources [72].

In addition to the refined oil, the distillate is obtained during the refining process, known as vegetable oil deodorization distillate (VODD). It is a by-product of the industrial processing of vegetable oils and is considered a low-cost source rich in health-giving components, such as tocopherols and phytosterols, in addition to FFA with numerous industrial applications. The distillates from physical refining have FFA contents above 70% and lower levels of unsaponifiable materials [73].

The research team of the Laboratory of Oils and Fats of the Faculty of Food Engineering—UNICAMP, Campinas, Brazil, studied the distillates from the deodorization of macauba kernel and pulp oils from physical refining. The kernel distillate presented 14.49 mg/100 g of γ-tocopherol and 0.79 mg/100 g of γ-tocotrienol. In turn, the pulp distillate presented 80.27 mg/100 g of γ tocopherol, 25.84 mg/100 g of β tocopherol, and 5.64 mg/100 g of γ tocotrienol (unpublished data).

According to Tay et al. [74], the free fatty acid content of palm oil deodorized distillate ranged from 72.7% to 92.6%. The author studied the co-product of palm oil refining and found VODD content of 86.4% [74]. These valuable components can be used in food, pharmaceutical, and cosmetic formulations [73].

3.4 Emerging technologies

The great potential of macauba has led to the development of several processing technologies for kernel and pulp oils. Favaro et al. studied the aqueous extraction of oil from fresh macauba pulp using the commercial enzyme Cellic® CTec3 and reported that the aqueous extraction was effective for obtaining high-quality oil [75]. Rosa et al. evaluated the effectiveness of ethyl acetate as a solvent in macauba kernel oil extraction by ultrasound-assisted extraction. Increasing the amount of solvent, the higher temperatures, and longer extraction times led to a higher amount of oil extracted [76]. Trentini et al. extracted macauba pulp oil by low-pressure solvent extraction and reported higher yields by using isopropanol as a solvent [77]. Prates-Valério et al. [78] studied different mechanical extraction conditions for obtaining pulp oil, aiming to produce an extremely productive raw material. The fruit pressed at 34°C resulted in higher oil quality when compared to other temperatures studied [78]. Favaro et al. evaluated the extraction efficiency and quality of pulp oil extracted using aqueous media from wet fruits and reported an acidity of 0.45% oleic acid [79]. Malaquias et al. estimated macauba yield by regression models using the variables bunch volume, length, and length/diameter ratio [80]. Colombo et al. studied the physicochemical characteristics of macauba and reported the high potential of this fruit [5].

3.5 Lipid modification processes

To meet market demands and provide varied and uniform raw materials, lipid modification processes allow flexibility and contribute to reducing the gap between production site, demand, and availability. The most commonly used modification processes include hydrogenation, fractionation, and interesterification, using analytical or computational methods to ensure process efficiency [20, 69].

3.5.1 Fractionation

The fractionation process consists of a thermomechanical separation in which the lipid material is separated into two or more fractions with different physical and chemical properties, due to the difference in the melting point of triacylglycerols. A fraction called olein is obtained, composed of a greater amount of triacylglycerols with a lower melting point, which is present in liquid form, and a semisolid fraction called stearin, composed of triacylglycerols with a higher melting point [81, 82]. Magalhães et al. [83] performed the fractionation of macauba kernel oil and evaluated the olein and stearin fractions for thermal behavior and consistency. The authors concluded that fractionation allowed obtaining fractions with different degrees of oxidative stability and different physical properties for various applications [83].

3.5.2 Hydrogenation

The presence of double bonds interferes with the chemical and physical properties of oils and fats. The hydrogenation reaction is a physicochemical process that leads to the saturation of the double bonds of unsaturated fatty acids through the addition of hydrogen atoms [20, 69].

Hydrogenation takes place in hermetic tanks, in which hydrogen gas is mixed with the raw material in the presence of a nickel catalyst, at high temperatures and high pressure. During partial hydrogenation, part of the double bonds of fatty acid is saturated, while some *cis* double bonds undergo isomerization and are converted to *trans*. A fully hydrogenated oil or fat is obtained after the hydrogenation of all double bonds. Fully hydrogenated vegetable oils are currently the technological alternative to produce fats with specific functional properties through both chemical and enzymatic interesterification reactions [84].

Various harmful effects have been associated with the consumption of *trans* fat in foods since these isomers are structurally similar to saturated fats, competing with essential fatty acids in complex metabolic pathways. In addition, they are cited as lipids that act as risk factors for coronary artery disease. Several countries have established changes in legislation, including Brazil through the Resolution (RDC) 332/2019, which sets limits on industrial fats for the food industry, with a ban on the use of partially hydrogenated fat until 2023 [85, 86]. The Pan American Health Organization launched an action plan to eliminate industrial *trans* fatty acids between 2020 and 2025, and in 2018 the World Health Organization warned the world about the need to remove these fats from the global food supply [87].

3.5.3 Interesterification

The interesterification of liquid oils and fully hydrogenated vegetable oils has been the main alternative to produce fats with specific properties [84]. During the reaction, although the fatty acids remain unchanged, there is a redistribution of fatty acids in the triacylglycerol molecules, leading to changes in the triacylglycerol composition [88].

Two technological processes can be used for the interesterification of oils, including chemical and enzymatic interesterification. The chemical interesterification uses an alkaline catalyst, with no control over the fatty acid distribution, that is, it has a random nature. In turn, the enzymatic interesterification uses lipases with specific activities and selectivity, thus with greater control over the fatty acid distribution in triacylglycerol molecules [89]. Our research group developed interesterified fractions from macauba oil, which led to a patent application with the National Institute of Intellectual Property (INPI), registered under the number BR 102020 026665 9 [89].

4. Potential for macauba applications

A. aculeata, in growing regions, is widely used by the local population, from the stem, leaves, and thorns to all parts of the fruit (epicarp, mesocarp, and endocarp) for food, medicinal, and craft purposes [90], while the medicinal applications of macauba palm as an analgesic, hypotensive, and diuretic are empirical [90]. Recently, a phytochemical study of the components of *A. totai* spines allowed the identification of eight bioactive compounds with anticancer, antiparasitic, antibacterial, and antiviral activities [91].

The macauba potential for industrial applications is due to the high productivity and quality of pulp and kernel oils and can be grouped into four industrial segments, such as pharmaceuticals, cosmetics, food, and energy [15].

Both the macauba pulp and kernel are edible and have high nutritional value, allowing their insertion into the food industry [15]. The pulp can be added directly to food or as flour [92]. Other parts of the fruit can also be used. The biomass resulting from the macauba oil extraction is pressed to form cakes as an alternative for animal feed, as they do not present toxic components [93]. The pulp cake contains 9% protein, while the kernel cake has 32% [15]. Residues from the oil extraction from the macauba endocarp have been used for the production of higher quality vegetable carbon when compared to carbon from eucalyptus, with wide application in the steel industry [5, 94].

The differential composition of macauba pulp and kernel oils concerning the fatty acid profile and minor components (tocopherols, carotenoids, antioxidants, and phenolic compounds) provides a differentiated market for both products [15]. Pulp oil has a higher content of oleic and linoleic acids, with a recognized role in disease prevention and health promotion, including the role of oleic acid in the prevention of breast cancer and linoleic acid in the cognitive abilities of the elderly [95, 96]. Additionally, the macauba pulp oil has a higher content of carotenoids and tocopherols when compared to kernel oil. Traesel et al. reported no cytotoxic, genotoxic, or mutagenic effects of macauba pulp oil in rats [97].

Studies have shown that pulp oil, both in its raw and microencapsulated form, has diuretic and anti-inflammatory potential. It was also found that the microencapsulated pulp oil maintained the stability of the active ingredient and exhibited antiedematogenic activity [98]. Recent research has suggested that macauba pulp oil can be a promising high-quality raw material for the production of functional ingredients and foods with nutraceutical properties [99].

The kernel oil presents high content of saturated fatty acids (74%) with a predominance of lauric acid (44%) [99], which can be a promising approach for use in the pharmaceutical and cosmetic industries [9]. Studies have shown the hypoglycemic effect of kernel oil in rats with type 2 diabetes when administered orally [100]. Dario et al. showed that kernel oil can be an alternative adjuvant in the development of a nanocarrier, enhancing the photoprotective activity [101]. Macauba kernel oil has also shown potential for use as a lipid ingredient in margarines and mayonnaises [102].

The macauba mesocarp oil is a promising raw material for biodiesel production due to the predominance of unsaturated fatty acids (±73%), mainly oleic acid (±52%) [14]. Biodiesel is defined as methyl esters of long-chain fatty acids derived from vegetable oils or fats [103]. As reported by Coimbra and Jorge, biodiesel derived from *A. aculeata* pulp oil is mainly composed of intermediate alkyl esters (16- and 18-carbon fatty acid chains) consisting of more than 50% monounsaturated alkyl esters, and approximately 25% palmitic acid esters [14]. This chemical composition ensures the desired thermo-oxidative stability and viscosity [104]. Currently, the industrial production of biodiesel is accomplished by alkali-catalyzed transesterification of vegetable oils in the presence of short-chain alcohol to form fatty acid esters and glycerol [105]. Meanwhile, macauba pulp oil has been used for the synthesis of ethyl esters by transesterification using both heterogeneous and homogeneous acid catalysts [106, 107]. Enzymatic transesterification reactions have also been used as a sustainable alternative to the chemical process for the production of biofuels from macauba pulp oil and ethanol [108]. Non-catalytic transesterification of macauba pulp oil in supercritical alcohols also generates quality products and environmental benefits [109]. These methodologies are more tolerant to high levels of oil acidity, which is common in macauba oil, while basic transesterification requires a maximum acidity of 0.5% (w/w) [105].

Xavier and Costa [15] performed a scientific and technological mapping on the characteristics and applications of macauba oil, showing the important contribution of Brazil in this area, and the participation of Brazilian universities in the valorization of native raw material. The technological segments most represented in this analysis of patents were energy, cosmetics, and agriculture [15].

5. Conclusions

Macauba is an emerging species with scientific interest concerning the distribution and genetic diversity of the species, plant development, oil production, crop management, harvest techniques and fruit treatment, extraction, processing, and modification of oils to obtain more plastic lipid bases for various applications. The high productivity of the macauba and the resilience of the crop along with the need to search for vegetable oils with potential use as alternative raw materials for biofuel production have encouraged further studies on this species. Although it is a very promising plant for the sustainable production of vegetable oil on a large scale, there are still scientific and technological challenges. The main challenges include obtaining commercial varieties, developing sustainable cultivation models, efficient fruit processing techniques, standardized refining protocols, and effective analytical techniques for oil characterization. This chapter summarizes the recent studies on *A. aculeata* biology, oil processing, and technological applications. To the best of our knowledge, this is the first comprehensive review of all the processing steps of *A. aculeata* oils (pulp and kernel) from fruit to refined oils, and the characterization of by-products of the refining distillate, thus addressing the entire macauba oil production chain.

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Conflict of interest

The authors declare no conflict of interest.

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