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Impact of different bio-fertilizers, seaweed extract and nutrients on the production of oilseed crops: A review

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Abstract
Oilseed crops are a diverse group of plants that include sunflower, canola, soybean, and rapeseed. They supply essential fatty acids and are a good source of essential carbohydrates, and vitamins A, D, E, and K. The oil cakes and oil meals are excellent sources of protein (40–60%) for both humans and animals. Oilseeds are integral to global agriculture due to their multifaceted utility in providing edible oils, biofuels, and industrial raw materials. Achieving sustainability in the production of oilseed crops is crucial as agricultural systems face challenges from climate change, degraded soil, and limited resources. The objective of this review is to compile the most recent findings regarding the development, yield, and quality of oilseed crops through the use of various bio-fertilizers, seaweed extracts, and nutrient management techniques. Through a thorough examination of the literature, this review explores the roles of nitrogen-fixing bacteria and phosphate-solubilizing bacteria in improving soil fertility and nutrient availability to oilseed crops. Additionally, it investigates the potential of seaweed extracts to stimulate plant growth, improve stress tolerance, and raise yield by activating defense mechanisms and regulating hormones. The results highlight the potential for boosting oilseed crop productivity through the integration of bio-fertilizers, seaweed extracts, and nutrient management techniques as sustainable substitutes to conventional chemical inputs. It demands further research and planning to create specialized agronomic techniques for enhancing the sustainability and resilience of oilseed crop production systems worldwide.

Keywords: Biofertilizers, seaweed extract, soil fertility, phosphorus solubilizing bacteria, nitrogen fixing bacteria

Introduction

In the world's agricultural produce hierarchy, oilseed crops rank fourth only to cereals, vegetables, fruits, and nuts [8]. India, the fourth largest oilseed producer in the world, has 20.8% of the total area under cultivation globally, accounting for 10% of global production. The country produces nine oilseed crops under the diverse agro-ecosystems among which soybean (34%), groundnut (27%), rapeseed and mustard (27%) contribute to more than 88% of total oilseeds production, and more than 80% of vegetable oil with a major share of mustard (35%), soybean (23%) and groundnut (25%). The production of oilseeds in India has been growing for the last five years. In 2022-23, the country's production was 40.9 million tonnes. From 2015-16 to 2022-23, production's compound annual growth rate (CAGR) was 5%. This was achieved due to the implementation of various programs like special programs on mustard and rapeseed during *rabi* and cluster demonstrations of improved technology by the Government of India [47]. Oilseed production is mainly restricted to rainfed areas and poor input resources (Reddy *et al.*, 2016) [35]. Increased productivity of oilseed crops on marginal soils under rainfed conditions through the adoption of improved management technology and improved germplasm would contribute to increased national self-sufficiency of edible oil (Pasricha, N. S. 2010) [29]. One of the key components that determines both the quantity and quality of agricultural products is plant nutrition. The groundbreaking technique Nobel Laureate Norman Borlaug developed on applying chemical fertilizers to crops that met the world's nutritional needs led to notable yield increases for almost a century (Noulas *et al.*, 2023) [28]. The significance of each of these crop nutrition management techniques advocates for an integrated approach to crop nutrition management, which would be more cost-effective and environmentally friendly to increase yields and, consequently, food security (Ali *et al.*, 2008) [2]. By integrating the best features of organic and inorganic nutrient sources, INM contributes to sustainable agriculture, improved soil health, and enhanced crop productivity. The nutrient management strategies that we adopt currently are fully dependent on chemical-based fertilizers, that supply nutrients in higher concentrations and pose a major risk to the environment and public health, on the other hand, small amounts of nutrients are continuously supplied by biofertilizers. Using bio-fertilizers aids in the secretion of substances that promote growth, improving root development, water transportation, and nutrient uptake and breakdown. Applying biofertilizers will improve soil health, reduce environmental pollution, increase organic agriculture, and require less input for oilseed crops (Noulas *et al.*, 2023) [28]. The overuse of chemical fertilizers negatively affects the fertility, productivity, and other micronutrients of the soil. The integrated application of inorganic fertilizers along with organic manures and bio-fertilizers alters the nutritional status of the soil, which further enhances food grain yield, soil fertility, and boosts farmer income (Pooniyan *et al.*, 2022) [33]. Biofertilizers are distinct from chemical and organic fertilizers in that they are made up of cultures of particular bacteria and fungi, which solubilize and mobilize the nutrients and enhance nutrient uptake efficiency, rather than providing nutrients to crops directly (Wahane *et al.*, 2020) [45]. Biofertilizer PSB solubilizes unavailable phosphorus present in soil and makes it available to plants, while a bacterium called *Azotobacter* is responsible for non-symbiotic nitrogen fixation in the soil (Gudadhe *et al.*, 2005) [10]. Different types of microorganisms are used as bio-fertilizers. The biofertilizers *Acetobacter*, *Azospirillum*, and *Azotobacter* are important for nitrogen fixation, while biofertilizers *Bacillus* sp. and *Aspergillus* sp. are important for phosphate solubilization and other soil mineral nutrients (Wahane *et al.*, 2020) [45]. Significantly more seeds were produced for the Toria crop as a result of *Azotobacter* and PSB seed inoculation (Bilal and Singh 2022) [5]. The results of two years of research suggest the implementation of integrated nutrient management practices, which include 100% of the recommended doses of N and P fertilizers overlaid with *Azotobacter* and PSB seed inoculation to increase mustard's productivity and profitability (Singh *et al.*, 2010-11 and 2011-12) [41]. Incorporation of sulfur fertilization @ of 30–60 kg/ha improves the growth, yield, nutrient uptake, and economics of oilseed crops (Nagaram I.P. 2020) [14]. The highest oil content in the seed was due to the application of sulfur @ 60 kg ha^{-1} as SSP (Sao Yushma& Pradhan Amit Kumar (2022) [38]. It is essential for the production of proteins, oils, and vitamins (Chahal *et al.*, 2021) [7] and also sulfur-containing amino acids which are necessary components in protein synthesis, including cystine, cysteine, and methionine (Patel *et al.*, 2019) [30]. Apart from nutrients, plants are also provided with other substances that promote growth, such as hormones, vitamins, and amino acids. These substances are known as bio-stimulants. One of the most promising classes of biostimulants is seaweed extract. Seaweed extract is a great organic manure that is safe for the environment and a substitute for inorganic chemical fertilizers to maintain crop productivity. The majority of seaweed species, such as *Ascophyllum, Fucus, Laminaria, Sargassum, Turbinaria, Kappaphycus, Sarconema,* and *Gracilaria,* are used to prepare see weed extracts, which improve the growth, yield, and quality of cereal, pulse, vegetable, and fruit crops (Margal *et al.*, 2023) [22]. Seaweed fertilizer is a good substitute source of nutrients for organic and sustainable crop production because it acts as a natural plant growth accelerator (Meng *et al.*, 2022) [23]. Seaweed extracts are rich in micro and macronutrients, polysaccharides, proteins, polyunsaturated fatty acids, polyphenols, phytohormones, and osmolytes (Hayyawi *et al.*, 2020) [3]. The integration of inorganic fertilizers, biofertilizers, and seaweed extracts represents a promising strategy for sustainable agriculture, offering multifaceted benefits for plant productivity, soil health, and environmental stewardship. Seaweeds have a wide range of advantages when used in agriculture, including promoting seed germination, improving plant health and growth (particularly elongating the shoots and roots), enhanced absorption of water and nutrients, resistance to frost and salinity, biocontrol and resistance to phytopathogenic organisms, removal of pollutants from contaminated soil, and fertilization (Nabti *et al.*, 2017) [26]. The application of bio-fertilizer, and inorganic soil amendments with foliar seaweed extract had a high agronomic value because of its ability to progressively release nutrients for plants and enhance soil properties by raising the total bacterial count, CO2 evolution, and soil microbiological activity. These properties increase the quantity and quality of sunflower seeds (Habashy, N. R., &Bishara, M. M. 2013) [11]. The use of both seaweed extract and inorganic sources of plant nutrients was most advantageous for increasing sesame growth and yield components. Similarly, the application of 15% *Gracilaria* sap + recommended dose of fertilizer recorded maximum growth attribute, seed yield, and nutrient uptake in sesame crop (Shankar *et al.*, 2011-12) [40]. The use of seaweed extracts granular and foliar greatly increased yield and yield-related characteristics. The highest yield attributes, seed yield, GMR, and NMR, were recorded with applications of 100% RDF + 40 kg SG ha^{-1} + 2 ml SL lit^{-1} seaweed extract in soybean crop (Patil *et al.*, 2017) [31]. Higher yield and benefit-cost ratios were observed in soybean when seaweed sap (at 20%) was applied in conjunction with 60 kg/ha of phosphorus. (Kumawat, P., & Dawson 2022) [19]. The Aquasap (Brand name of AquAgri for bio-stimulant of seaweed *K. alvarezii*) significantly increased the seed yield and oil content of peanut by 31.69% and 14.27%, similarly on sunflower the increase in seed yield and oil content was 51.50 and 15.77% respectively (Karthikeyan, K., & Shanmugam, M. (2015) [15]. Kiruthika *et al*., (2022) reported that application of 75% RDF + poultry manure @ 10 t ha^{-1} through soil application along with foliar application of 15% seaweed extract at 30 and 60 DAS and harvest stages recorded maximum soil nutrient availability [17]. The synergistic effects of integrating these inputs lead to improved nutrient uptake, enhanced crop yield and quality, and reduced reliance on synthetic chemicals. To optimize the advantages of combining inorganic fertilizers, biofertilizers, and seaweed extracts in the future, more studies and the implementation of integrated nutrient management strategies are necessary.

'The effect of different biofertilizers and nutrients on growth and growth attributes of oilseed crops

Gudadhe *et al.*, (2005) reported that seed inoculation of mustard (*Brassica juncea* L.) with *Azotobacter* + PSB along with 100% RDF (40:20:0) kg ha^{-1} recorded the highest value for the plant height (156.3 cm) and dry matter accumulation (29.6 g) [10]. Vijayeswarudu C.Y.N.A and Singh Rajesh (2020) conducted a field experiment on yellow mustard (*Sinapis alba)* at SHAUTS Prayagraj, the results showed that treatments receiving PSB + 45 kg S hac^{-1} recorded the highest value for the plant height (94.46 cm), branches (10.60), and dry weight (23.71 g) [44]. Samant Kumar Tiryak (2014-15 and 2015-16) found maximum plant height (91.33 cm), number of branches per plant (4.69), and dry matter accumulation (467.06 gm^{-2}) at harvest for both years on sesame crop were recorded in (75% STD + *Azospirillum*, *Azotobacter* & PSB @ 4 kg each incubated with 300 kg of FYM ha^{-1} at 30% moisture for 7 days + Sulphur @ 30 kg ha^{-1}) conditions [36]. Sandhya *et al.*, (2021) found that (30 kg/ha of Sulphur through SSP + *Azotobacter*) has recorded the highest plant height of 134.90 cm, while the highest leaves (23.40) were reported by (30 kg/ha of Sulphur through gypsum + *Azospirillum*) and (30 kg/ha of Sulphur through SSP + *Azospirillum*) has recorded maximum dry weight of 13.02 g at harvest in sunflower [37]. Hadiyal *et al.*, (2015-16) revealed that application of biofertilizer had a significant impact on the number of primary and secondary branches per plant and combined inoculation with *Azotobacter* spp. + PSB spp. (each @ 10 ml/kg seed) produced the highest value of growth parameters in mustard [12]. Beenish *et al.*, (2016-17 and 2017-18) observed that (50% N through vermicompost + *Azotobacter*) exhibited significantly higher plant growth *viz*., Plant height 142.14 cm in 2016 and 143.34 cm in 2017 over other treatments in Rani variety of Indian mustard [4]. Patra *et al.*, (2009-2010 and 2010-2011) found that the total amount of chlorophyll and plant height were greatly impacted by the biofertilizer inoculation in hybrid sunflowers. PSB + VAM + *Azotobacter* inoculation resulted in noticeably higher plant heights and also compared to S @ 0 and 20 kg ha^{-1}, the application of S @ 40 kg ha^{-1} resulted in noticeably higher plant heights and was at par with S @ 60 kg ha^{-1}, during both years [32]. Kalita *et al.*, (2015-16 and 2016-17) experimented on Toria (TS-36) variety in farmers' fields of the Karbi Anglong district of Assam and stated that (*Azotobacter* + PSB + 75% of recommended NPK + FYM) had the highest plant height (88.52 cm), number of branches $plant^{-1}$ (4.93), and root dry weight (2.30 g) as compared to (recommended NPK) and (recommended NPK + FYM), better root growth has been achieved in treatment receiving (*Azotobacter* + PSB + 75% NPK + FYM) and (*Azotobacter* + PSB + 50% NPK + FYM) [14]. At (Varanasi) Uttar Pradesh, the application of combined inoculation of *Azotobacter* + PSB + 100% N and P_2O_5 significantly improved the growth parameters *viz*. plant height, number of primary and secondary branches, number of functional leaves, leaf area index, dry matter accumulation, and chlorophyll content in Indian mustard under irrigated conditions. (Singh *et al.*, 2010-11 and 2011-12) [41]. Saini *et al.*, (2016) recorded (*Azotobacter* + PSB + 30 kg ha^{-1} N through inorganic Fertilizer + 30 kg ha^{-1} N through Organic manure poultry manure (PM) produced significantly higher plant height 75 Days (95.53 cm), number of branch $plant^{-1}$ (8.37), dry weight (15.58 g) in Toria mustard [20]. At Prayagraj (U.P.) application of *Azotobacter* and PSB along with the application of Phosphorus-50 kg/ha recorded the highest plant height (124.54 cm), plant dry weight (25.01 g/plant), number of branches (11.71) in Toria crop. (Bilal and Singh 2022) [5]. At Latur (Maharashtra), plant height (171.20 cm), no· of functional leaves (27.33), stem girth (7.96), leaf area (50.67 dm^2), leaf area index (2.81) were favorably influenced by the application of (100% N + *Azospirillum* + *Azotobacter*) in *kharif* sun flower on clayey soil. (Khandekar *et al.*, 2016-17) [16]. Mahammad *et al.*, (2011-12) reported that 100% RDF + *Azotobacter* + PSB was found to be significantly superior in respect of plant height, number of branches $plant^{-1,}$ and dry matter accumulation $plant^{-1}$ in linseed crop [34]. At Kanpur, (Uttar Pradesh) seed inoculation with *Azotobacter* @ 5 ml + PSB @ 5 ml kg^{-1} seed had given significantly higher growth attributes, *viz*., plant population, plant height (cm), fresh weight (g), dry weight (g), number of branches $plant^{-1}$ in mustard (Kumar *et al.*, 2021-22) [18]. Treatment receiving dual inoculation of *Azotobacter* and PSB + vermicompost 5 t/ha + 50% RDF recorded higher values for plant height (210.47 cm), primary branches/plant (9.40), no· of secondary branches/plant (19.03), and dry matter accumulation (99.10 g/plant) in Indian mustard. (Bhanuwanti *et al.*, 2020-21) [9]. Singh *et al.*, (2013-14) reported that sulfur dose @ 60 kg/ha significantly influenced the plant growth (plant height, no of branches/plant, leaf area index) which was at par with 30 and 45 kg S/ha in the mustard crop [42]. Habashy N. R and Bishara M.M. (2013) observed that the highest values of all the tested plant growth characters s (i.e., the total leaf of chlorophyll, plant height, number of leaves $plant^{-1}$ and dry matter weight $plant^{-1}$) were obtained by applying seaweed foliar, P-dissolving bacteria, and elemental sulfur to the soil at a rate of 450 kg fed^{-1} [11]. Shankar *et al.*, (2011-12) reported the highest plant height (102.50 cm), dry matter (185.20), and CGR (3.86), in sesame crop with the application of (15% *Gracilaria* along with 100% RDF). [40]. The highest plant height (69.01 cm), no· of branches per plant (18.07), plant dry weight (24.05 g), and crop growth rate (21.16 g/m^2/day) in soybean crop was produced with combined application of seaweed sap 20% along with phosphorus 60 kg/ha. (Kumawat Pawan and Dawson Joy 2022) [19]. Jawale *et al.*, (2018-19) conducted a field experiment and found that application of seaweed extract (20%) + organic plant extract (80%) at the flowering and developing stage recorded higher growth attributes and was at par with brassinosteroids (0.01%) + organic plant extract. [13]. Kumar *et al.*, (2012-13) revealed significant improvements in Growth parameters *viz*. plant height, and no· of branches with the application of *Gracilaria* sap (G sap) as compared to *Kappaphycus* (K sap) in sesame crop [6]. Mirparsa *et al.*, (2015) conducted an experiment in factorial with randomized complete block design and observed that maximum plant height in sunflower was obtained under *Azotobacter*-1 + Potassium fertile 2 + Seaweed application [24].

The effect of different biofertilizers and nutrients on the yield and quality of oilseed crops

Seed inoculation with *Azotobacter* and PSB along with 100% RDF (40:20:00 NPK kg ha^{-1}) significantly increased number of siliquae $plant^{-1}$, number of seeds $siliqua^{-1}$, test weight, and recorded the highest seed yield (1266 kg ha^{-1}) and straw yield (2982 kg ha^{-1}) as compared to 75% RDF + *Azotobacter* + PSB (Gudadhe *et al.*, 2005) [10]. Sandhya *et al.*, (2021) recorded the maximum no. of seeds/ capitulum (375.33) and test weight (39.20 g) in treatment T_6 (30 kg/ha of Sulphur through SSP + *Azotobacter*). The treatment T_6 has recorded a maximum grain yield of 1495.67 kg/ha and the highest stover yield of 3255.33 kg/ha in sunflower [37]. Hadiyal *et al.*, (2015-16) recorded that inoculation of mustard seeds with *Azotobacter* spp. + PSB spp. (each @ 10 ml/kg seed) significantly increased numbers of siliqua per plant, numbers of seed per siliqua, seed yield and stover yield in mustard [12]. Beenish *et al.*, (2016-17 and 2017-18) reported that 50% N through vermicompost + seed inoculation with *Azotobacter* gave significantly higher no· of siliqua/plant, no· of seeds/siliqua, test weight, and seed yield (q/ha) and stover yield (q/ha) in Rani variety of Indian mustard. The quality parameters such as protein yield and oil yield were found to be significantly higher in the above treatment [4]. At Kolhapur (Maharashtra), the application of 125% RDF (31.25:62.5:0) $kgha^{-1}$ produced noticeably higher dry pod yields (24.95 q ha^{-1}) and dry haulm yields (35.48 q ha^{-1}) in groundnut, which also produce significantly higher oil yield (953.87 kg ha^{-1}), protein content in groundnut kernels (24.75%), and protein yield (469.34 kg ha^{-1}).In effect of various bio-fertilizer treatments, dual inoculation of *Rhizobium* spp. + PSB (Lignite based) produce significantly the highest dry pod yield (24.42 q ha^{-1}) and dry haulm yield (34.32 q ha^{-1}) and also the quality contributing characteristics like oil yield (922.39 kg ha^{-1}), protein content in groundnut kernels (24.90%), and protein yield (463.33 kg ha^{-1}) over control and was on par with dual-seed inoculation with *Rhizobium* spp. + PSB (Liquid-based) (Satpute *et al.*, 2019) [39]. Prakash Ajnar and Suvarna Namdeo (2019-20) experimented on Indian Hybrid Mustard NRCHB 506, it was observed that highest number of siliqua $plant^{-1}$ (461.0), maximum no. of seeds $siliqua^{-1}$ (14.93) and test weight of seed significantly increased in treatment T9 (75% RDF + S @ 40 kg ha^{-1} + Vermicompost @ 5 t ha^{-1} + *Azotobacter* + PSB). Treatment T_9 also recorded the highest stover yield as well as seed yield followed by treatment T_8 75% RDF + S @ 40 kg ha^{-1} + Vermicompost @ 5 t ha^{-1} [1]. Patra *et al.*, (2009-2010 and 2010-2011) found that the application of sulfur and the use of biofertilizers had an impact on oil content, harvest index, biological yield, seed yield, and stalk yield, in comparison to the inoculation of PSB + *Azotobacter* and VAM + *Azotobacter*, the inoculation of PSB + VAM + *Azotobacter* exhibited a noteworthy impact on grain yield, stalk yield, biological yield, harvest index, and oil content in hybrid sunflower [32]. Kalita *et al.*, (2015-16 and 2016-17) found that the treatment involving *Azotobacter* and PSB + 75% NPK yielded the highest test weight (4.92), the maximum number of siliqua $plant^{-1}$ (164.76), and the maximum number of seeds (10.17) in comparison to *Azotobacter* + PSB + 50% NPK, followed by recommended NPK + FYM and recommended NPK in Toria crop [14]. At (Varanasi) Uttar Pradesh, seed inoculation with *Azotobacter* + PSB significantly increased yield attributes *viz*. siliquae/plant, length of siliqua, seed/ siliqua, and 1000-seed weight and harvest index. The application of *Azotobacter* + PSB + 100% N and P_2O_5, which remained at par with 100% (N and P_2O_5) and *Azotobacter* + PSB with 75% N and P_2O_5 /ha in both the experimentation years, resulted in a higher seed and stover yield. The dual inoculation of seed with *Azotobacter* + PSB + 50% (N + P_2O_5) resulted in the highest oil content in Indian mustard (Singh *et al.*, 2010-11 and 2011-12) [41]. Yadav *et al.*, (2003-04) reported that the maximum increase in yield was obtained by application of sulphur @ 40 kg ha^{-1} and biofertilizer @ 200 g *Azotobacter* per 10 kg seed inoculate (S2B1) in Indian mustard [46]. Saini *et al.*, (2016) observed markedly increased yield under the conditions of (*Azotobacter* + PSB + 30 kg ha^{-1} N through inorganic fertilizer + 30 kg ha^{-1} N through poultry manure (PM) with respect to the number of siliqua plants (235.33), number of seed siliqua plants (20.40), test weight (4.17 g), seed yield (1500 kg ha^{-1}), stead yield (3790 kg ha^{-1}), harvest index (28.36%), and oil content (42.03%) [20]. At Prayagraj (U.P.) application of *Azotobacter* and PSB along with the application of Phosphorus-50 kg/ha recorded the highest number of siliqua (232.53 cm), seeds/siliqua (20.60), test weight (3.92 gm), higher grain yield (20.6 q/ha) and higher stover yield (3.70 t/ha) in toria (Bilal and Singh 2022) [5]. At Latur (Maharashtra), application of 100% N + *Azospirillum* + *Azotobacter* recorded the highest seed yield (1848 kg ha^{-1}) with net monetary return (Rs 34,313) and B: C ratio (1.96) in kharif sunflower. (Khandekar *et al.*, 2016-17) [16]. At Baruipur (West Bengal), a two-year experiment revealed that the application of VC (2.5 t ha^{-1}) or FYM (5 t ha^{-1}) with *Azotobacter*, PSB, and 50% recommended doses of chemical fertilizers in alluvial soil with foliar spray of 2% urea was the best possible combination for higher seed yield in sunflower. (Mukherjee *et al.*, (2013-14 and 2014-15) [25]. Mahammad *et al.*, (2011-12) reported that the application of 100% RDF + *Azotobacter* + PSB was at par with100% RDF + *Azotobacter*, 100% RDF, and 75% RDF + *Azotobacter* + PSB and registered maximum seed yield (9.91 q ha^{-1}) and straw yield (15.56 q ha^{-1}) and oil yield (4.27 qha^{-1}) in linseed crop [34]. At Udaipur (Rajasthan), seed inoculation with PSB along with phosphorus @ 50 kg ha^{-1} and sulfur @ 50 kg ha^{-1}obtained maximum grain and stover yield. (Solanki *et al.*, 2012-13 and 2013-14) [43]. At Kanpur, (Uttar Pradesh) seed inoculation with *Azotobacter* @ 5 ml + PSB @ 5 ml kg^{-1} seed had given significantly higher yield attributes *viz*., number siliqua $plant^{-1}$, number of seeds $siliqua^{-1}$, test weight, and grain yield, stover yield, biological yield and harvest index (%) in mustard. (Kumar *et al.*, 2021-22) [18]. Bhanuwanti *et al.*, (2020-21) recorded highest seeds/siliqua (13.90), siliqua/plant (371.63), length of siliqua (5.17 cm), 1000 seed weight (6.00 g), and as well as seed yield (2.28 t/ha) and straw yield (2.03 t/ha) under dual inoculation of *Azotobacter* and PSB + vermicompost 5 t/ha + 50% RDF [9]. Singh *et al.*, (2013-14) reported that with increasing doses of sulfur up to 60 kg/ha, seed yield, stover yield, and sulfur content in seed and stover increased significantly and were comparable with 45 kg S/ha in mustard. [42]. Habashy N. R. and Bishara M.M. (2013) showed that the application of elemental sulfur in conjunction with either P-dissolving bacteria or seaweed extract significantly improved the head diameter, 100 seed weight, seed yield, and some parameters of seed quality (oil and protein contents) [11]. Shankar *et al.*, (2011-12) revealed that the highest number of capsules $plant^{-1}$, branches $plant^{-1}$, seed $capsule^{-1}$ were recorded with the application of (15% *Gracilaria* along with 100% RDF) in sesame crop [40]. At Parbhani (Maharashtra), granular and Foliar applications of seaweed extract gave highest seed yield (2232 kg ha^{-1}), straw yield (2879 kg ha^{-1}), biological yield (5111 kg ha^{-1}) and harvest index (%) of soybean with the application of 100% RDF + 40 Kg SG ha^{-1} + 2 ml SL lit^{-1} twice during flowering and pod filling stage. (Patil *et al.*, 2017) [31]. Higher no. of pods per plant (126.27), maximum no. of seeds per pod (3.0), seed index (8.73 g), seed yield (2.39 t/ha), oil content (19.33%), and protein content (38.28%) in soybean crop was produced with the application of seaweed sap 20% along with phosphorus 60 kg/ha. (Kumawat Pawan and Dawson Joy 2022) [19]. At Raipur (Chhattisgarh), in "*Vertisol*" soil type foliar spray of 15% Seaweed sap of *Kapaphycus* spp + RDF @ (20:60:40:20 Kg/ha for N:P:K:S) revealed a noteworthy impact on dry matter (40.32 g), seed index (10.37 g), seed yield (2510 kg ha^{-1}), and protein yield in soybean crop. (Lodhi Kamal Kant and Diwan Uttam Kumar 2013) [21]. Jawale *et al.*, (2018-19) revealed that applying seaweed extract (20%) and organic plant extract (80%) during the flowering and pod-developing stages of soybean growth would be a promising practice for yield and yield qualities [13]. Kumar *et al.*, (2012-13) showed a substantial increase in seed yield 283.0 kg/ha in K-Sap + RDF (40:20:20 NPK/ha) and 297.5 kg/ha in G-Sap + RDF, obtained from 5% sap solution, which was comparable to that of 10% sap solution, which produced 291.4 kg/ha of seed yield in K-Sap and 309.1 kg/ha in G-Sap [6]. Mirparsa *et al.*, (2015) conducted an experiment in factorial with randomized complete block design and observed that maximum grain yield, test weight, and head weight in sunflower was obtained under *Azotobacter*-1 + Potassium fertile 2 + Seaweed application [24].

The effect of different biofertilizers and nutrients on soil health under oilseed crops

Hadiyal *et al.*, (2015-16) revealed that the use of biofertilizers aids in the secretion of substances that promote growth, which improves mustard root development, water transportation, and nutrient uptake and breakdown [12]. Beenish *et al.,* (2016-17 and 2017-18) reported that for the best possible growth of crop plants, the combined application of organic and inorganic fertilizers stimulates and showed the accumulation of specific metabolites [4]. Prakash Ajnar and Suvarna Namdeo (2019-20) reported that the application of (75% RDF + S @ 40 kg ha^{-1} + Vermicompost @ 5 t ha^{-1} + *Azotobacter* + PSB) is the optimal combination for integrated nutrient management in mustard crops that improve soil properties and have a major impact on all growth parameters [1]. Patra *et al.,* (2009-2010 and 2010-2011) reported that in agricultural soils, phosphorus is frequently a limiting nutrient. Microorganisms are an essential component of the soil P cycle because they are engaged in various processes that influence how soil P is transformed. Phosphorus Solubilizing microorganisms (bacteria or fungi) can solubilize unavailable soil P and increase the yield of crops [32]. Yadav *et al.,* (2003-04) observed that the interaction between sulfur (gypsum as source) and biofertilizer (*Azotobacter*) showed an increase in organic carbon, available nitrogen, phosphorus, potassium, and sulfur in the soil sample collected after harvest in Indian mustard [46]. Mukherjee *et al.,* (2013-14 and 2014-15) reported higher soil chemical, microbiological, and biochemical parameters by the combined application of organic and inorganic fertilizers, which also enhanced sunflower seed yields [25]. Mahammad *et al.,* (2011-12) revealed highest residual available nitrogen, phosphorus, and potassium in soil was present due to the application of 100% RDF + *Azotobacter* + PSB [34]. The application of phosphorus, sulfur, and PSB either alone or in combination resulted in an increase in organic carbon, available nitrogen, phosphorus, potassium, and sulfur after the harvest of the mustard. (Solanki *et al.,* 2012-13 and 2013-14) [43]. Habashy N. R. and Bishara M.M. (2013) revealed that inoculation with P-dissolving bacteria, in combination with application of 450 kg fed^{-1} elemental sulfur and foliar seaweed extract, demonstrated the highest values of CO2 evolution, dehydrogenase activity, and bacterial count [11]. Kiruthika *et al.,* (2022) reported improved nutrient status of the gingelly-grown sandy loam soil by the integrated application of seaweed extract, organic manure, biofertilizers, and inorganic fertilizers and recorded the highest availability of macro and secondary nutrients [17].

The effect of different biofertilizers and nutrients on the economics of different oilseed crops

Sandhya *et al.,* (2021) reported that (30 kg/ha of Sulphur through SSP + *Azospirillum*) has recorded maximum gross and net return of 160233.33 and 111752.3 INR/ha respectively, while highest B: C ratio (1.4645) was obtained by T_8 (30 kg/ha of Sulphur through gypsum + *Azotobacter*) in sunflower crop [37]. Hadiyal *et al.,* (2015-16) recorded that seed inoculation with bio-fertilizers *Azotobacter* and PSB (each @ 10 ml/kg seed) (B_3) gave the highest net returns of 86629 Rs/ha and B:C ratio of 3.40 in mustard [12]. Satpute *et al.,* (2019) observed that when compared to 75% RDF, the application of 125% RDF produced noticeably higher gross monetary returns (Rs 130569 ha^{-1}) and net monetary returns (Rs 72347.86 ha^{-1}). However, under the impact of different bio-fertilizer treatments, the highest economic return of groundnut gross monetary returns (Rs 127769.48 ha^{-1}) and net monetary returns (Rs 69632.58 ha^{-1}) was obtained due to dual inoculation of *Rhizobium* spp. + PSB (Lignite based) over control as compared to *Rhizobium* spp. + PSB (Liquid-based) [39]. Kalita *et al.,* (2015-16 and 2016-17) observed T3 (*Azotobacter* and PSB + 75% NPK) produced the highest net return (Rs. 17605 ha^{-1}) and had the maximum B: C ratio of (2.11). Application of *Azotobacter* and PSB in combination with 75 and 50% NPK and FYM @ 2 t ha^{-1} could be an effective and practical way to increase the yield and generate a profit from toria farming in the hill zone of Assam [14]. At (Varanasi) Uttar Pradesh, (Singh *et al.,* 2010-11 and 2011-12) recorded the maximum gross return (Rs 29,680 and Rs 43,282), and net return (Rs 15,717 and Rs 25,600), with *Azotobacter* + PSB + 100% N and P_2O_5, however maximum output: input ratio (1.16 and 1.50) was recorded under *Azotobacter* + PSB + 75% N and P_2O_5 in Indian mustard under irrigated conditions [41]. Saini *et al.,* (2016) recorded the highest gross return (67740 ha^{-1}), net return (33265 ha^{-1}), and benefit-cost ratio (1.96) in (*Azotobacter* + PSB + 30 kg ha^{-1} N through inorganic Fertilizer + 30 kg ha^{-1} N through poultry manure (PM) [20]. Mahammad *et al.,* (2011-12) recorded maximum gross monetary returns (Rs 37658 ha^{-1}), net monetary return (Rs 21722 ha^{-1}), and B: C ratio of 2.36 due to the application of 100% RDF + *Azotobacter* + PSB in linseed crop [34]. Patil *et al.,* 2017 observed that the application of 100% RDF + 40 kg SG (granule) + 2 ml SL (liquid) seaweed extracts gave maximum gross return (Rs. 70,955 ha^{-1}), and net return (Rs. 37,280 ha^{-1}) and highest B: C ratio (2.14) in 100% RDF + 20 kg SG + 2 ml SL in soybean crop [31]. Application of seaweed sap 20% along with phosphorus 60 kg/ha recorded maximum gross return (1,42,037.93 INR/ha), net return (1,01,073.53 INR/ha) and benefit cost ratio of (2.47) in soybean crop. (Kumawat Pawan and Dawson Joy 2022) [19]. Kumar *et al.,* (2012-13) revealed that the highest net returns and B: C ratio was recorded with GSap 10% and 5% (Rs.8671 and Rs.8350) 1.87 which was at par with KSap net returns and B: C ratio with 10% and 5% (Rs.7609 and Rs. 7480) with 1.77 and 1.78 in sesame crop [6].

Conclusion

The effect of various bio-fertilizers, seaweed extract, and nutrient combinations on oilseed crop production varies depending on soil type, climate, and specific formulations used. Bio-fertilizers can increase soil fertility and encourage plant growth, by adding beneficial microorganisms to the soil. Seaweed extract is a natural product derived from various species of seaweed or marine algae, when applied to crops stimulates root development, improves nutrient uptake, enhances resistance to environmental stresses such as drought and disease, and promotes overall plant vigor. Nutrient combinations play a crucial role in sustaining the growth and development of plants and influencing factors such as flowering, fruit set, and yield. Overall, the application of these inputs contributes to sustainable agricultural practices by reducing the need for synthetic fertilizers and pesticides which results in increased crop yields, improved soil health, and enhanced resilience to environmental stressors. Therefore, the appropriate combinations of nutrients act as a valuable tool for farmers seeking to optimize crop production, promote ecosystem health, minimize environmental impact, and achieve food security.

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