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Oilseed Brassica Species Diversification and Crop Geometry Influence the Productivity, Economics, and Environmental Footprints under Semi-Arid Regions

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Citation: Rathore, S.S.; Babu, S.; Shekhawat, K.; Singh, V.K.; Upadhyay, P.K.; Singh, R.K.; Raj, R.; Singh, H.; Zaki, F.M. Oilseed Brassica Species Diversification and Crop Geometry Influence the Productivity, Economics, and Environmental Footprints under Semi-Arid Regions. *Sustainability* **2022**, *14*, 2230. https://doi.org/10.3390/su14042230

Academic Editor: Teodor Rusu

Received: 14 November 2021
Accepted: 14 January 2022
Published: 16 February 2022

Abstract: The article presents the findings of three-year field experiments conducted during 2017–2020 on the productivity, economics, and environmental footprints of the oilseed Brassica (OSB) with species diversification and crop geometry alterations in semi-arid regions of India. The objectives of the field experimentation was to assess the system of mustard intensification (SMI) in enhancing productivity and profitability with ensuring fewer environmental footprints. The results revealed that *Brassica carinata* gave a maximum seed productivity (3173.8 kg ha^{-1}) and net returns (US$ 1141.72 ha^{-1}) under a crop geometry of 60 cm × 60 cm. Further, an increase of 38% and 54% in seed yield and net returns from *B. carinata* was observed over the existing traditional *Brassica juncea* with conventional crop geometry. The maximum energy output was also recorded from *B. carinata* (246,445 MJ ha^{-1}). The broader crop geometry (60 cm × 60 cm) also resulted in maximum energy output. The environmental footprint was lesser due to increased carbon gain (CG), carbon output (CO), and carbon production efficiency (CPE) and lower greenhouse gas intensity (GHGi) in *B. carinata*. However, the maximum water-use efficiency (WUE) was recorded in *B. juncea* (19.15 kg per ha-mm), with a minimum water footprint (WFP), whereas, greater crop geometry (60 cm × 60 cm) resulted in lower WFPs and better irrigation water use. Enhanced seed yield, economics, and fewer environmental footprints were observed at broader crop geometry in *B. carinata* over remaining OSBs.

Keywords: carbon sustainability; greenhouse gas emission; oilseed brassica; edible oil; system of mustard intensification; water footprint

1. Introduction

Oilseed Brassicas (OSB) are important edible oil crops, which broadly include rapeseed-mustard. These are the leading vegetable edible oil sources, after oil palm and soybean, in the world [1]. In India, OSBs are the most-preferred edible oil and are produced in large quantities domestically [2]. India imports edible oil worth more than USD 10.0 billion annually to meet the national requirement. India has the second-largest arable area (145 Mha) in the world, but ironically more than 70% of the net sown area is devoted for graminaceous cereal-millet cultivation. The concerted efforts have revolutionized cereal production in the country and made it self-reliant in food grain production. However, the increasing gap in edible oil demand and supply has become a cause of concern. Severe environmental tradeoffs are occurring due to higher acreage under water-guzzling and high-nutrient-demanding crops in India and elsewhere. Crops like oilseeds and pulses are proven climate-smart crops [3] due to their lower environmental footprint and relatively low greenhouse-gas emissions (GHGs) due to low input needs. OSBs includes seven crops that are mainly used for the extraction of edible oil. These are Indian mustard (*Brassica juncea* (L.), black mustard (*Brassica nigra*), Toria (*Brassica campestris* L. var. toria), brown sarson (*Brassica campestris* L. var. brown sarson), yellow sarson (*Brassica campestris* L. var. yellow sarson), and taramira (*Eruca sativa/vesicaria* Mill.), along with non-traditional species like gobhi sarson (*Brassica napus* L.) and Ethiopian mustard or karan rai (*Brassica carinata*). Oilseed rape (*Brassica napus*) with canola quality, i.e., low-glucosinolate, low-erucic acid varieties, represents one of the world's major sources of vegetable oil. It is the major edible oil in many countries like Australia, Japan, and Canada [3]. Rapeseed and mustard are grown worldwide, having maximum acreage in Canada (8 Mha) followed by China (7 Mha) and India (6.8 Mha). Contrary to the global trend of having larger areas under rapeseed, Indian mustard (*Brassica juncea* L.) is the predominant cultivated OSB in India. The OSB productivity in India is lower (1.16 Mg ha^{-1}) compared to the global average (2.14 t ha^{-1}) due to a huge technological gap existing between potential and actual productivity [2,4,5]. The European Union has the highest OSB productivity (3.64 Mg ha^{-1}), and higher OSB productivity in Europe and North America is attributed to the long crop duration and better carbon content in the soil [6].

Initial agronomic evaluation in many countries has established the usefulness of *B. carinata* as a prospective edible oilseed crop worldwide and especially in India [7]. However, its inclusion in many of the rapeseed-mustard-based cropping systems in the subtropics remains limited due to the longer crop-duration restriction [3,4,7]. In Mediterranean regions and in India, *B carinata* has been highlighted as a promising winter crop by many researchers for high oil yield [8–12]. The multifarious usage of *B. carinata* for edible oil, biofuel production, and industrial purposes makes its marvel crop. It is presently being cultivated in northeast Africa, some parts of Canada, France, Spain, Australia, China, India, and in South America. Another oilseed rape (*Brassica napus* L.) has greater prospects, which can also be a potential option to substitute cereal crops areas due to its higher productivity and its comparable economics. *Brassica napus* (gobhi sarson) is mainly grown in America and Europe, is popularly known as canola (Canada oil), and is used to label rapeseed varieties that are low in erucic acid and glucosinolate in extracted edible oil [13]. Gobhi sarson is presently under cultivation over a limited area in Himachal Pradesh, Jammu, and Kashmir and Punjab under irrigated production systems. OSB including *B. napus* and Ethiopian mustard/Karan rai are the emerging oilseed crops having a limited area under cultivation in northern India [14], but the long duration remains a major constraint. Among the various OSBs cultivated in India, Indian mustard is the predominant winter oilseed crop due to its adaptability in the existing cropping system under rainfed areas. It also accounts for >75% of the total area under rapeseed-mustard cultivation in India. Evaluation of improved agronomic practices like the system of mustard intensification (SMI) that could improve yields needs to be standardized. The SMI for non-traditional OSBs in India must also be optimized under square geometry with specific establishment methods [15].

The positive effects of growing oilseed rape in a cereal-based system have been extensively described [16–18] for their affirmative impact on the agroecosystem via subsoil amelioration leading to enhanced nutrient and water uptake and disease suppression in the following cereal [16]. Currently, many researchers are keenly probing an oilseed crop as a resilient OSB [19], wherein *Brassica carinata* is the best candidate to withstand varied vulnerable environmental conditions [20,21]. It is also one of the most-promising Brassicacae crops, which can be used currently for energy production [8,22] and for phytoremediation properties as well [23,24]. Its higher production potential necessitates fewer inputs, and its ability to adapt to and survive abiotic and biotic challenges makes it valuable in terms of agronomy and energy balances [25]. Besides being a good source of edible oil, OSB crops have been widely documented for having a better carbon budget [7,26–28]. Crop production, including forestry and other land use (AFOLU), accounts for 24.8 percent of global greenhouse-gas (GHG) emissions [29,30]; hence, the selection of crops and cropping systems requires careful planning to keep an optimum C balance in arable soils. The soil carbon pool (2500 gigatons or 10^{12} kg) is >3.0 times larger than the atmospheric carbon pool (760 GT) [31,32]. Deep-rooted arable crops, such as OSBs, are particularly important for sustaining this C pool in the soil. OSBs with a high biomass contribution and low input requirements thus become critical [4].

In addition, water use in agriculture has become a serious issue for sustainability as agriculture is the world's largest freshwater user, accounting for nearly all of the world's consumptive (green and blue) water footprint [33,34]. It has become a crucial need to shift from increasing agricultural production per unit of land to increasing agricultural productivity per unit of water to avoid future water scarcity. The proficient use of available water by rapeseed-mustard causes higher average water productivity (WP), which remains 0.85 kgm^{-3} in India. Brining rain-fed rapeseed and mustard areas under irrigation would suffice the crop's relatively low water needs effusively through two to three light irrigations [35–37]. Improved farming practices with species diversification under the SMI show promise under such circumstances to produce more from limited water and to enhance water-use efficiency [7,38]. Thus, rapeseed-mustard in SMI may be an effective approach, which can optimally enhance productivity and also the WUE and eventually reduce water and environmental footprints altogether. Keeping these sustainability challenges in the foreground, SMI has been evaluated with the transplanting of *B. napus* and *B. carinata* under a specific crop geometry to enhance the crop productivity, water-use efficiency, and energy usages under Trans-Indo Gangetic plain zones.

2. Materials and Methods

2.1. Experimental Site and Weather Conditions

To enhance productivity with lesser environmental footprints, field experiments on a system of mustard intensification (SMI) were conducted at the experimental field (Top Block), ICAR –Indian Agricultural Research Institute (IARI), New Delhi located at latitude 28°38′23′′ N, longitude: 77°09′27′′ E, and 228.61 m AMSL for three consecutive years (2017–2020). The climate of the experimental site was sub-tropical, and >70% of the total rainfall was received during July to October. July and August were the wettest months (>60% of monsoonal rainfall), while the remaining period in years were normally lesser or had scanty rainfall. The maximum rainfall was received in July (368.4 mm) during 2017–2018 (Figure 1).

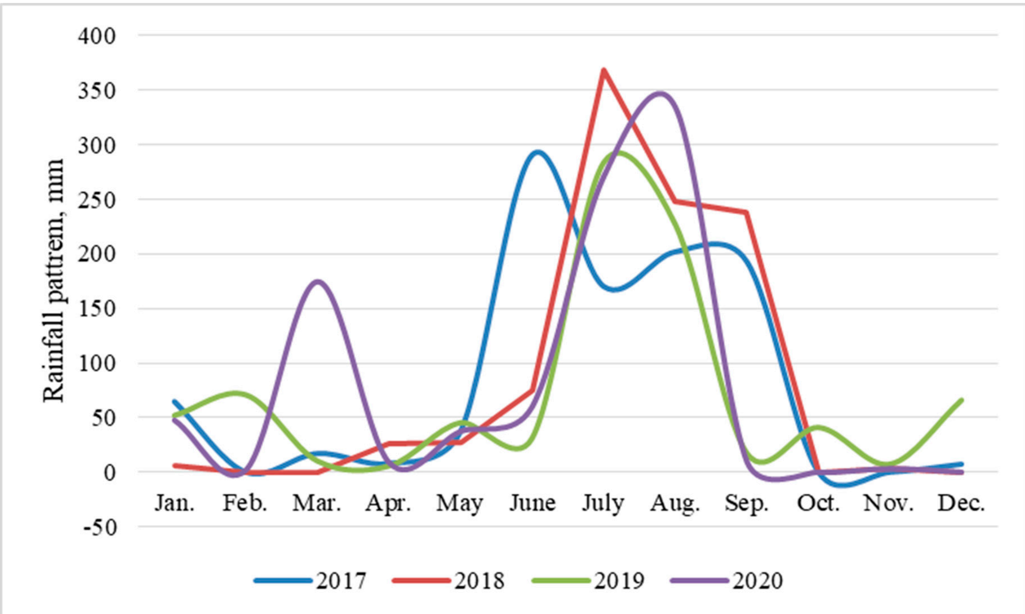

Figure 1. Rainfall pattern over the period of study (2017–2018 to 2019–2020).

A significant deviation in mean monthly maximum temperatures was also observed across the years. The minimum temperature remained stable, and the lowest temperature in all three years was recorded in January. The typic Haplustert soil of the experimental field was sandy loam (65% sand, 14% silt, and 21% clay) in texture, slightly alkaline in nature (pH 7.9), and low in carbon (0.40%), available nitrogen ($KMnO_4$ oxidizable N 151 kg ha^{-1}), phosphorus (0.5 M $NaHCO_3$-extractable P 12.6 kg ha^{-1}), and potassium (neutral 1 *N* NH_4OAc-extractable K 255 kg ha^{-1}).

2.2. Experimental Details

The field experiment was carried out with a two-factor split-plot design and three replications. OSB species *Brasica carinata (PC 6), Barssica napus (GSC 7)*, and *Brassica juncea* (var. Pusa Vijay) were sown in main plot, while a diverse crop geometry in sub-plots was used to ensure higher precision of the data. The direct seeded crop of *Brassica carinata* and *Brassica napus* often coincide with high temperature stress at the pod-filling stage, which reduces the seed yield. Similarly, early sowing in September or the first week of October faces high temperature at the germination stage, which causes the poor plant stand and lesser crop yield. Therefore, the seedlings were raised in the nursery (1000 m^2) for 30 days for transplanting in the main field. In sub-plots, the crop geometries included three configurations, i.e., 60 cm × 60 cm and 45 × 45 cm as transplanted oilseed brassica, and were compared with the standard practice of direct seeding at the 45 × 15 cm crop spacing. The experiment was laid out in a fixed-plot manner. Each OSBs were sown in a particular cropping system in the same plots during three years of experimentation (2017–2018, 2018–2019, and 2019–2020). The gross and net plot sizes were 5 m × 5 m and 4.5 m × 4.5 m, respectively. The soil preparation was done as per treatment, and recommended tillage operations were followed for direct seeded as well as the transplanted oilseed brassica. The nursery of *B. carinata* and *B. napus* was laid down during the second week of September year, and the transplanting in the main field was done by the first week of October. One irrigation immediately after transplanting was done to have a better chance of seedling survival. The details of inputs used and agronomic management adopted are given in Table 1.

2.3. Crop Management and Yield Measurements

The particulars of crop-management practices performed and input used in different OSB species were as per the recommended practices. The field was prepared as per crop requirements and the treatment imposed. One deep plowing with a disc harrow was followed by three plowings with cultivators. After plowing, planking was done as normal tillage operations. The sowing of seed in the nursery was done during the second week of September every year. The transplanting in the main field of the seedlings of *B. carinata* and *B. napus* was done during the second week of October. After transplanting of the seedlings in the main field, one light irrigation (40–50 mm) was applied for optimum seedling establishment. The direct seeding of *B. juncea* was done at the same time, i.e., during the second week of the October every year; the detailed operations are mentioned in Table 1.

The direct seeded *B. juncea* was irrigated twice in the crop-growth period: once at 30 days after sowing (DAS) and second at silique initiation (60–70 DAS). The need-based weed, disease, and insect management were practiced as explained in Table 1. The nutrient requirement was also different for all three OSBs, depending upon the total biomass yield and nutrient uptake. As per the recommended fertilizer dose, N, P, K, and S was applied. The whole amount of P, K, and S was applied as basal dose, while 1/2 N of the total requirement was applied as basal and the remaining 1/2 N was top-dressed after the first irrigation (40 DAS). The initial 30 DAS remained critical for crop weed completion in Indian mustard, while in the case of *B. napus* and *B. carinata*, the first 45 DAS remains crucial for weed interference; hence, the crop was kept weed-free through one pre-emergence spray of oxadiagryl (16%) @ 90.0 gm a.i.ha^{-1}, followed by two hand-weedings. The crop was harvested based on physiological maturity; accordingly, *B. napus* and *B. carinata* were harvested after 185 DAS (10–15 April every year), whereas *B. juncea* matured at 145 DAS and was harvested in and around 15 March. The agronomic operations were done as per crop needs and treatments.

Table 1. Input use in diverse Oilseed brassica species.

Operations	***B. carinata***	***B. napus***	***B. juncea***
Variety	*PC 6*	*GSC7*	*Pusa vijay*
Nursery and field preparation	Three ploughings followed by planking	Three ploughings followed by planking	Three ploughings followed by planking
Seed	2.5–3.0 kg ha^{-1}	2.5–3.0 kg ha^{-1}	5 kg ha^{-1}
Transplanting	30-day-old seedlings	30-day-old seedlings	-
Irrigation	Three irrigations (180 mm)	Three irrigations (180 mm)	Two irrigations (120 mm)
Fertilizer (N-P-K-S)	100-50-40-40	100-50-40-40	80-40-40-40
Herbicide	Oxadiargyl 16 @ 90 gha^{-1} and two hand-weedings	Oxadiargyl 16 @ 90 gha^{-1} and two hand-weedings	Oxadiargyl 16 @ 90 gha^{-1}
Insecticide	Need-based	Two sprays of Dimethoiate 30 EC @ 600 mL ha^{-1}	Two sprays of Dimethoiate 30 EC @ 600 mL ha^{-1}
Fungicide	Downy mildew endemic areas; the disease is managed by treating the seeds with metalaxyl-M 31.8% ES @ 6 mLkg^{-1} seed	Treating the seeds with metalaxyl-M 31.8% ES @ 6 mLkg^{-1} seed	Soil incorporation of Trichoderma based product @ 2.5 kg ha^{-1} pre- incubated in 50 kg of well rotten farm yard manure to reduce soil-borne inoculum of Alternaria blight, white rust, downy mildew, club root, and Sclerotinia rot.
Harvesting and threshing	At physiological maturity	At physiological maturity	At physiological maturity

The seed yield of the individual OSB crops were assessed by harvesting 20.25 m^2 areas under each crop at maturity. The economic part (seed) of all OSB crops were winnowed and cleaned after harvesting with a Pullman plot thresher. The grain yield of rapeseed-mustard was estimated at an 8% moisture content.

2.4. Productivity and Production Efficiency Estimation

The productive capacity of different OSBs species was estimated in terms of total seed output from one ha area. The net plot area (20.25 m^2) crop plants were included in estimation of seed yield per ha. The biological productivity was estimated as total aboveground biomass accumulation including both the seed as well the vegetative part of the crop plants.

The ability of the system to produce economic yield per day is known as production efficiency (PE) and was estimated as per Equation (1).

$$\text{PE}\ (\text{kg ha}^{-1}\ \text{day}^{-1}) = \frac{\textit{Total seed yield}\ \left(\text{kg ha}^{-1}\right)}{\textit{crop duration}(\text{Days})} \tag{1}$$

2.5. Carbon-Emission and C- Efficiencies Estimation

Carbon emissions from different management and cropping systems refer to the total greenhouse-gas emissions. Total greenhouse-gases emission includes the emission from transportation, production, and all inputs for crop required during the entire crop production series from sowing to harvest and the direct N_2O emissions from the farm soil. The carbon emissions from different management practices in the present study was estimated using the following formula.

$$\text{CE} = \sum_{i=1}^{n} CE_i + CE_{N2O} = \text{cm} \sum_{i=1}^{n} \sigma_i\ \times\ C_i + C_N\ \times \sigma_{N2O}\ \times 1.57 \times 298 \times 0.27 \tag{2}$$

where the carbon emission of each production input (kg ce ha^{-1}) is denoted by CE; σ *i* is the carbon-emission parameters of each production input *i*; *Ci* is the amount of each production input *i*; *CE* N_2O represents the carbon footprint caused by direct N_2O emissions from application of N fertilizer (kg ce ha^{-1}); CN is the quantity of N fertilizer (kg ce ha^{-1}) applied; σN_2O is the emission factor of N_2O emissions induced by N-fertilizer application; 1.57 factor concerning with molecular weight of N_2 and N_2O; 298 is the net global warming potential (GWP) in a 100-year horizon; 0.27 factor concerning to the molecular weight of CO_2 and *CE*.

The reduction in carbon emissions remains essential for the design of carbon-neutral production systems. Hence, improving the efficiency of resource use in crop production is very crucial. To assess the carbon neutrality of designed production systems, the following C indices were calculated. For carbon input auditing, specific C-equivalence factors as recommended by the IPCC were multiplied with the respective input used.

Net C gain was calculated with the Equation (3)

$$\textit{Net C emission}\ \left(kg\ CO_{2\ e}\ Mg^{-1}\right) = CS - CE \tag{3}$$

where *CS* is the photosynthesis carbon sink (kg ce ha^{-1}), and *CE* is the total carbon emission equivalence (kg ce ha^{-1}) Carbon ecological efficiency (CEE) is the ratio of photosynthetic carbon to total carbon emissions produced in the specific production system. A production system with a higher CEE is considered more sustainable over others. Similarly, carbon production efficiency (CPE) and carbon economic efficiency (CEcoE) measured the food productivity and economic gain per unit of carbon emission, respectively. CEE, CPE, and CEcoE were calculated with the Equations (5)–(7), respectively.

$$\text{CEE} = \frac{\text{Carbon sin k of photosynthesis } (\text{kg ce ha}^{-1})}{\text{Total carbon emission } (\text{kg ce ha}^{-1})} \tag{4}$$

$$\text{CPE} = \frac{\text{Economic output } (\text{kg ha}^{-1})}{\text{Total carbon emission } (\text{kg ce ha}^{-1})} \tag{5}$$

$$\text{CEcoE} = \frac{\text{Total economic value } (\text{US\$ ha}^{-1})}{\text{Total carbon emission } (\text{kg ce ha}^{-1})} \tag{6}$$

$$\text{GHGI} = \frac{\text{GWP } (\text{kg ce ha}^{-1})}{\text{Seed yield } (\text{kg ha}^{-1})} \tag{7}$$

2.6. Carbon Sustainability Index (CSI)

It indicates the C efficiency potential of a production system. The systems had higher CSI considered as C-efficient systems. The CSI was calculated as per Equation (8) [39].

$$Is = \left(\frac{\mathrm{C_0} - \mathrm{C_i}}{\mathrm{C_i}}\right)t \tag{8}$$

where *Is* indicates the carbon sustainability index; $\mathrm{C_0}$ is the sum of all C outputs, expressed in C equivalents; $\mathrm{C_i}$ is the total C inputs in terms of C equivalents; and t is the time in years.

2.7. Energy Estimation

Energy auditing is a key tool to judge the environmental performance of the production system. Environmental emissions are directly linked with energy consumption, and the estimation of energy use in crop production explores an energy-use efficiency edge between outputs and inputs [40]. The energy input includes both direct and indirect energy. Energy use in crop cultivation is form of fuel for machinery, human and animal power, and electric power used, whereas indirect energy use consists of planting material, nutrient sources, and pesticide uses. Energy computations were done with the help of energy coefficients [41–44], and their multiplication with the level of specific input was used for crop cultivation. Likewise, for estimation of energy output, energy coefficients were integrated with the economic production of a specific crop in the system [41,44–47]. For energy dynamics auditing in OSB, energy indices were used to assess the energy efficiency in the study:

$$\text{Net Energy } (\text{MJ ha}^{-1}) = \text{Energy output } (\text{MJ ha}^{-1}) - \text{ Energy input } (\text{MJ ha}^{-1}) \tag{9}$$

$$\text{Energy Efficiency} = \frac{\text{Total energy output } (\text{MJ ha}^{-1})}{\text{Total energy input } (\text{MJ ha}^{-1})} \tag{10}$$

$$\text{Energy productivity} = \frac{\text{Net energy returns } (\text{MJ ha}^{-1})}{\text{Total energy input } (\text{MJ ha}^{-1})} \tag{11}$$

$$\text{Specific energy } (\text{Kg MJ}^{-1}) = \frac{\text{Energy input } (\text{MJ ha}^{-1})}{\text{Economic yield } (\text{Mg ha}^{-1})} \tag{12}$$

2.8. Water Use and Water Footprint

The measured quantity of irrigation water was applied to each OSB species. Water-use efficiency, water productivity, and the water footprint were calculated based [7,48] on the equations given below.

$$Irrigation\ WUE\ (\text{kg}^{-1}\ per\ ha - mm) = \frac{\text{Seed productvity } (\text{Kg ha}^{-1})}{\text{Irrigation water applied } (\text{ha} - \text{mm})} \tag{13}$$

$$Water\ productivity\ (kg\ seed\ per\ \mathrm{m}^3\ water) = \frac{\text{Seed productivity } (\text{kg ha}^{-1})}{\text{Irrigation water applied } (\text{m}^3)} \tag{14}$$

$$Water\ footprint\ (Liters\ of\ water\ per\ \mathrm{kg}^{-1}\ seed) = \frac{\text{Water used } (\text{liters ha}^{-1})}{\text{Seed productivity } (\text{kg ha}^{-1})} \tag{15}$$

2.9. Economic Analysis

The economic analysis of the diverse OSBs under different crop geometries was done based on the marginal analysis of the input and the output used. The crop-management practices and input used from sowing to storage of the products were used for estimation of the cost of cultivation of different crops. The gross return was estimated by multiplying the minimum support price declared by the Government of India with crop production. The net returns were calculated deducting the gross return from the cost of cultivation. The monetary outflow occurred, and returns attained from the crops in diversified production systems were done in USD (1 USD = ₹73.5). The system net returns (SNR), the benefit-cost ratio (B:C), and the profitability index (PI) were calculated by the following Equations (16)–(18).

$$\text{NR}\left(\text{US\$ ha}^{-1}\right) = \text{Gross returns (US\$)} - Cost\ of\ cultivation\ (\text{US\$}) \tag{16}$$

$$\text{B:C ratio} = \frac{Net\ return\ \left(\text{US\$ ha}^{-1}\right)}{Cost\ of\ cultivation\ (\text{US\$ ha}^{-1})} \tag{17}$$

$$\text{PI}\ (\text{US\$ ha}^{-1}\ \text{day}^{-1}) = \frac{Net\ returns\ (\text{US US\$})}{365} \tag{18}$$

2.10. Statistical Analysis

The general linear model (GLM) method of the SAS 9.4 (SAS Institute, 2003) was used for analysis of variance, using all data. This was also used for determining the statistical significance of the OSBs under diverse crop geometries under SMI. The least-significant difference (LSD) at $p = 0.05$ was used to compare the treatment effects.

3. Results

3.1. Effect on OSB Productivity and Economics

Among all the OSBs, *B. carinata* resulted in a maximum seed productivity (3173.8 kg ha^{-1}), which remained significantly higher over *B. napus* and *B. juncea*. Likewise, the crop geometry of 60 cm × 60 cm produced the highest seed productivity (2836.4 kgha^{-1}) but remained at par with a 45 cm × 45 cm crop geometry and significantly higher over a conventional crop geometry of 45 cm × 15 cm (Table 2 and Figure 2).

A similar trend was observed in the biological yield and the production efficiency of different OSBs under various crop geometries; however, the effect of crop geometry on production efficiency was found to be non-significant (Table 2). A 38% and a 9.3% higher seed yield were recorded in *B. carinata* and *B. napus*, respectively, over existing traditional Indian mustard cultivation with the prevailing crop geometry. Likewise, the crop geometry of 60 cm × 60 cm resulted in a 13% increase in seed yield, and up to a 5% higher growth was observed at a 45 cm × 45 cm crop geometry over traditional crop spacing. The economics of OSB species diversification indicates that the maximum net return of USD 1417 ha^{-1} was recorded from *B. carinata*, which was 54% higher over *B. napus* and 10% higher over *B juncea*. With regards to crop geometry, 60 cm × 60 cm resulted in a 12% increase, whereas the 45 cm × 45 cm crop geometry resulted in an almost 2% increase in the net return. In all the treatments, the B:C ratio remained greater than 2, however the maximum (3.76) was with *B. carinata*. Among *B. napus* and *B. juncea*, the B:C ratio remained statistically at par (2.71 and 2.45, respectively). The profitability index (PI) showed that the per-day net return was significantly higher (USD 7.66) in *B. carinata*, and the PI remained statistically at par with *B. napus* and *B. juncea* in all economic parameters including PI (Table 3). The care in the nursery at the early stage ensured greater survival of the seedlings and subsequently better crop stands by the end of October. The quick initial growth and timely maturity of the crop under the Indo Gangetic plains zones also skipped the terminal heat stress often faced with the late-sown crop.

Table 2. Seed, biological productivity (kg ha^{-1}), and production efficiency of Oilseed brassica under diverse crop geometries and crop-establishment methods.

Treatments	Seed Yield (kg ha^{-1})	Biological Productivity (kg ha^{-1})	Production Efficiency (kg ha^{-1} day^{-1})
Oilseed Brassica species-A			
B. carinata	3173.8 ^{A}	17,179 ^{A}	17.2 ^{A}
B. napus	2511.7 ^{B}	13,764 ^{B}	13.6 ^{B}
B. juncea	2298.4 ^{B}	12,012 ^{B}	15.9 ^{AB}
Crop geometry-B			
S1: 60 × 60	2836.4 ^{A}	15,559 ^{A}	15.9
S2: 45 × 45	2631.7 ^{A,B}	13,971 ^{B}	15.4
S3: 45 × 15	2515.9 ^{B}	13,425 ^{B}	15.3

Note: (Means followed by different letters in each column for particular set of treatments are significantly different at $p \leq 0.05$ as per Tukey's HSD test).

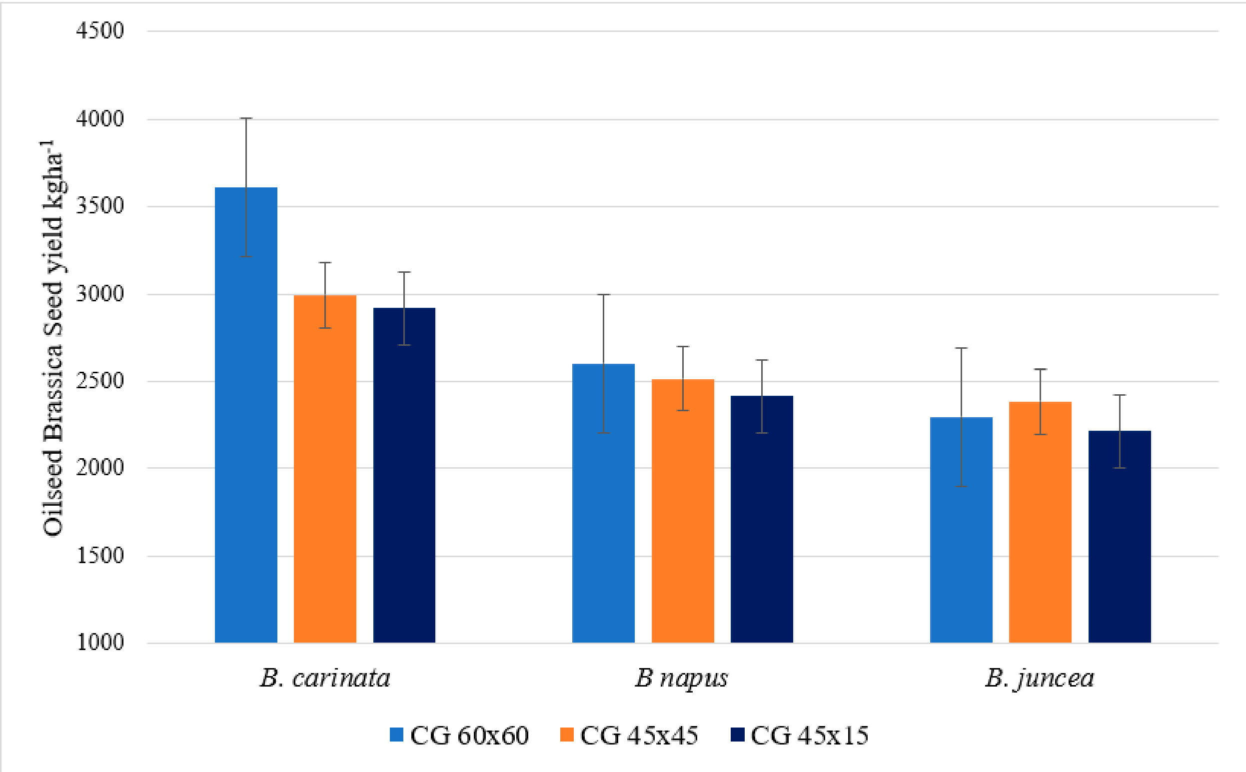

Figure 2. Effect of crop geometry and species diversification (SMI) on seed yield of OSB (CG. Crop geometry).

The intensive energy usage causes increasing costs, greenhouse-gas emissions, and other negative environment footprints; hence, efficient energy use has become very critical for agricultural operations at the present time. The energy studies revealed that the maximum energy output was obtained from *B carinata* (246,445 MJ ha^{-1}), which was significantly ($p \leq 0.05$) higher over *B. napus* and *B juncea*. Broader crop geometry (60 cm × 60 cm) also resulted in maximum energy output but remained statistically at par with 45 cm × 45 cm and higher than the energy output from traditionally grown *B juncea*. A similar trend was obtained in net energy, energy efficiency, energy productivity, and energy profitability (Table 4). However, the specific energy was greater in the case of *B. juncea* under a regular crop geometry (45 cm 15 cm). The declining trend of energy input likewise resulted in a lower specific energy under broad crop spacing (60 cm × 60 cm), whereas a narrow, regular crop geometry incurred a higher energy input and consequently a higher specific energy.

Table 3. Economics of Oilseed brassica under diverse crop geometries and crop-establishment methods.

Treatments	NR (US\$ ha^{-1})	B:C Ratio	Profitability Index (USD ha^{-1} day^{-1})
Oilseed Brassica species-A			
B. carinata	1417.2 ^{A}	3.76 ^{A}	7.66 ^{A}
B. napus	1018.9 ^{B}	2.71 ^{B}	5.51 ^{B}
B. juncea	920.5 ^{B}	2.45 ^{B}	6.35 ^{B}
Crop geometry-B			
S1: 60 × 60	1199.0 ^{A}	2.99 ^{A,B}	6.93 ^{A}
S2: 45 × 45	1089.6 ^{A}	2.72 ^{B}	6.36 ^{A}
S3: 45 × 15	1068.6 ^{A}	3.21 ^{A}	6.23 ^{A}

Note: (Means followed by different letters in each column for particular set of treatments are significantly different at $p \leq 0.05$ as per Tukey's HSD test).

Table 4. Energy-use dynamics of species diversity under diverse crop geometries (pooled).

Treatments	Energy Input (MJ ha^{-1})	Energy Output (MJ ha^{-1})	Net Energy (MJ ha^{-1})	Energy Efficiency	Energy Productivity	Energy Profitability	Specific Energy
Oilseed Brassica species-A							
B. carinata	8994 ^{A}	246,445 ^{A}	233,814 ^{A}	27.40 ^{A}	26.00 ^{A}	0.35 ^{A}	2.9 ^{B}
B. napus	8994 ^{A}	200,091 ^{B}	193,492 ^{B}	22.25 ^{B}	21.51 ^{B}	0.28 ^{B}	3.69 ^{A}
B. juncea	8382 ^{C}	172,872 ^{B}	162,707 ^{C}	20.62 ^{B}	19.41 ^{B}	0.27 ^{B}	3.71 ^{A}
Crop geometry-B							
S1	8790 ^{C}	224,492 ^{A}	213,714 ^{A}	25.45 ^{A}	24.23 ^{A}	0.32 ^{A}	3.24
S2	8790 ^{B}	203,731 ^{A,B}	194,223 ^{A,B}	23.13 ^{A,B}	22.04 ^{A,B}	0.3 ^{A,B}	3.44
S3	8790 ^{A}	191,185 ^{B}	182,077 ^{B}	21.69 ^{B}	20.65 ^{B}	0.29 ^{B}	3.61

Note: (Means followed by different letters in each column for particular set of treatments are significantly different at $p \leq 0.05$ as per Tukey's HSD test).

3.2. Carbon-Use Dynamics and Efficacy

The level of carbon input remained the same under all the OSB species under varying crop geometries. However, the carbon gain, the carbon output, and the carbon production efficiency (Figures 3 and 4) stand significantly higher under *B. carinata*. Similarly, a broader squared crop geometry at 60 cm × 30 cm resulted in a higher CG, CO, and CPE.

The GHGi was obtained higher in *B. juncea* OSB and lower in *B. napus* and *B. carinata*. However, crop geometry did not influence the GHGi in any of the OSB species. Carbon ecological efficiency (CEE) was significantly higher in *B. carinata* (14.9 DW ha^{-1} kg-eq CO_2) compared to Cecol E in *B. napus* and *B. juncea*, while CEE remained higher under a spacious crop geometry (Table 5). The carbon sustainability index was recorded as higher in *B. carinata*, but it remained statistically at par with *B. napus* and *B. juncea*. Broader crop spacing resulted in a higher CSI (5.07) over conventional spacing (Table 5).

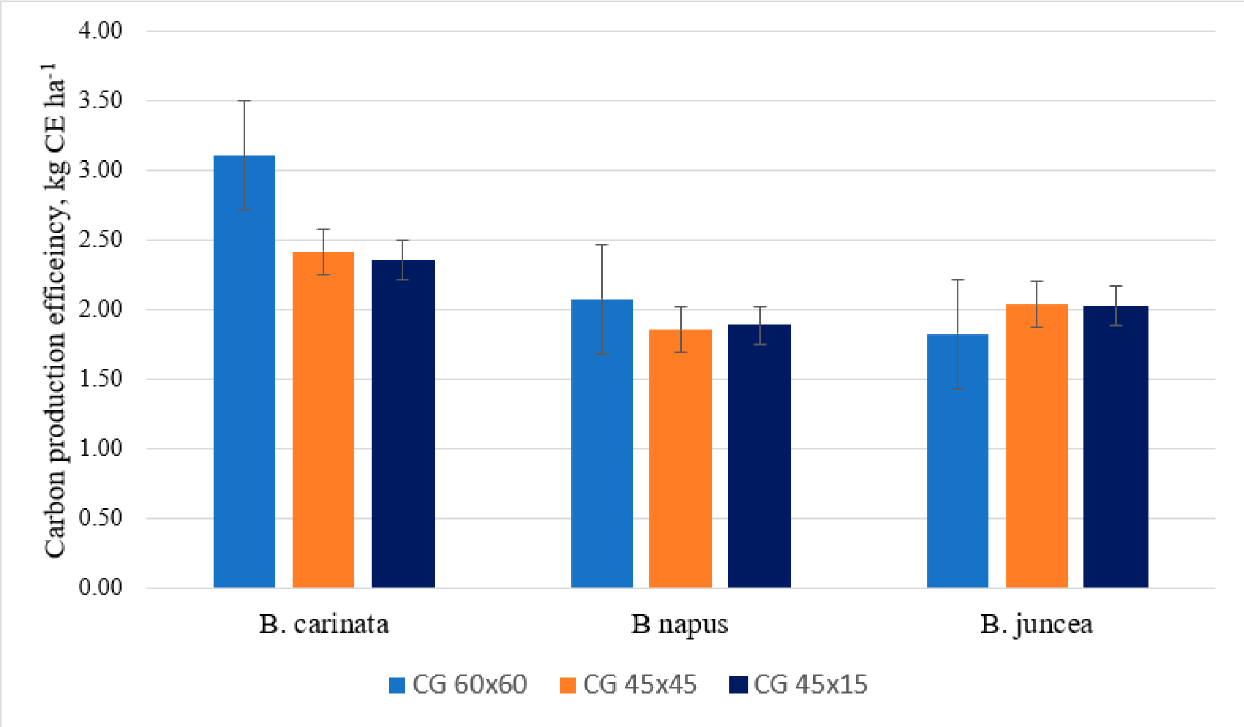

Figure 3. Effect of crop geometry and species diversification on the carbon-production efficiency of OSB (CG: crop geometry).

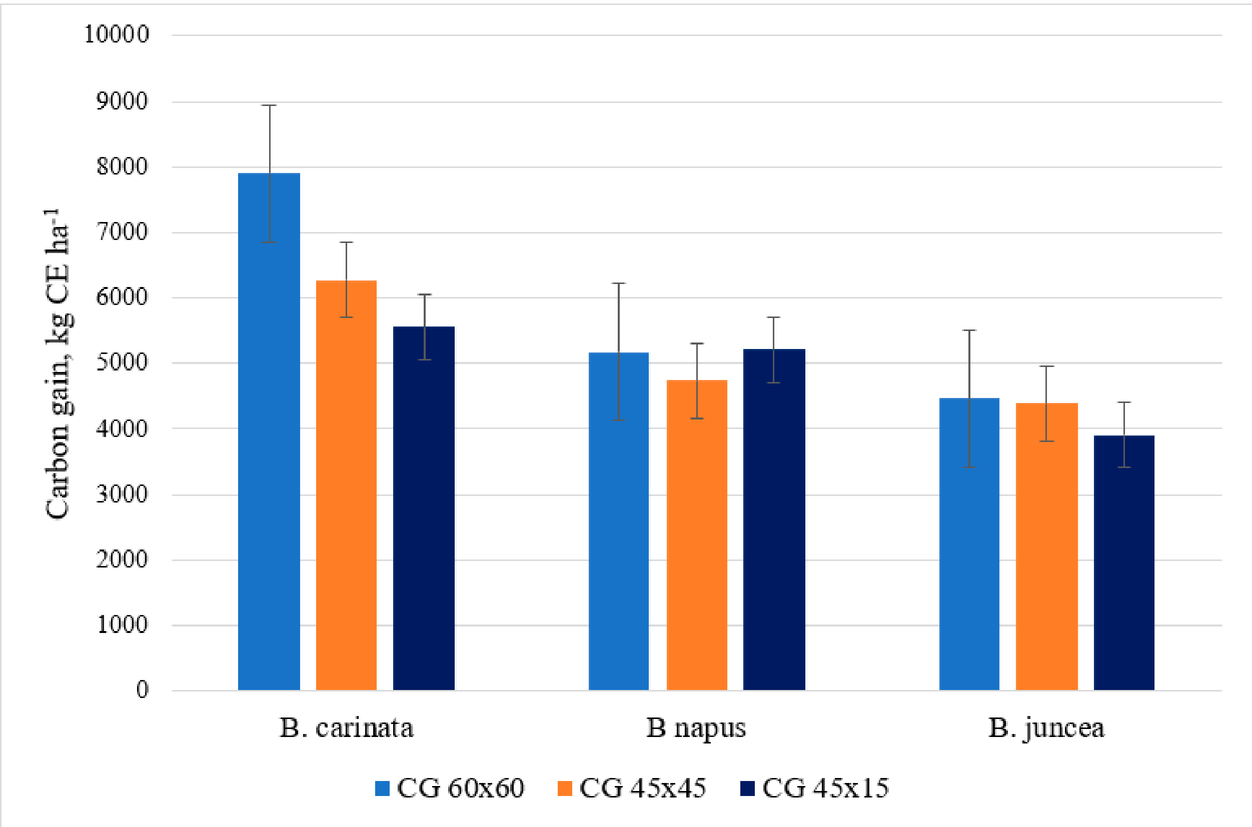

Figure 4. Effect of crop geometry and species diversification on the carbon gain under SMI of OSB (CG: crop geometry).

Table 5. Carbon analysis of diversification of Oilseed brassica under diverse crop geometry.

Treatments	Carbon Input (kg ha^{-1})	Carbon Gain (kg ha^{-1})	Carbon Output (kg ha^{-1})	CPE (Kg Seed CO_2-eq/ha^{-1})	GHGi (Kg CO_2-eq per kg^{-1} Grain Yield)	CEE (Kg per ha DW ha^{-1} kg-eq CO_2)	CEcoE (USD ha^{-1} CO_2-eq)	CSI
Oilseed Brassica species-A								
B. carinata	1152 ^{C}	6578 ^{A}	7730 ^{A}	2.63 ^{A}	0.37 ^{B}	14.90 ^{A}	1.24 ^{A}	5.71 ^{A}
B. napus	1152 ^{B}	5042 ^{B}	6194 ^{B}	1.95 ^{B}	0.47 ^{A}	11.94 ^{B}	0.89 ^{B}	4.38 ^{A,B}
B. juncea	1152 ^{A}	4253 ^{C}	5405 ^{BC}	1.97 ^{B}	0.51 ^{A}	10.42 ^{B}	0.80 ^{B}	3.69 ^{B}
Crop geometry-B								
S1	1154 ^{B}	5847 ^{A}	7002 ^{A}	2.34 ^{A}	0.43 ^{A}	13.48 ^{A}	1.05 ^{A}	5.07 ^{A}
S2	1154 ^{A}	5133 ^{B}	6287 ^{B}	2.11 ^{B}	0.45 ^{A}	12.10 ^{A,B}	0.95 ^{A}	4.45 ^{A,B}
S3	1148 ^{C}	4893 ^{C}	6041 ^{B}	2.09 ^{B}	0.47 ^{A}	11.69 ^{B}	0.94 ^{A}	4.26 ^{B}

Note: (Means followed by different letters in each column for particular set of treatments are significantly different at $p \leq 0.05$ as per Tukey's HSD test).

3.3. Water Usage and Efficiency

The WUE of applied irrigation water was found at a maximum in *B. juncea* (19.15 k per ha-mm), but it remained statistically at par with WUE of *B. carinata*, and the minimum WUE was recorded in *B. napus* (13.95 k per ha-mm). There was no effect of crop geometry on WUE and WP. The WP of *B. juncea* remained at par with *B. carinata*, whereas the minimum WP was recorded from *B. napus* (1.42 kg m^{-3}). The water footprint (WFP) was lowest in the case of *B. juncea*, which remained at par with *B. carinata*; however, the WFP of *B. napus* remained at 892.5 L for one kg of seed yield. The crop geometry under transplanting also influenced the WUE, WP, and WFP. The WUE under the broader crop geometry of 60 cm × 60 cm (17.88 kg per ha-mm) remained statistically on par with 45 cm × 45 cm but significantly higher over the conventional crop geometry of 45 cm × 15 cm (Table 6).

Table 6. Water-use efficiency, water productivity, and footprints of oilseed brassica under diverse crop geometries and crop-establishment methods.

Treatments	WUE_{IW} (kg ha^{-1}-mm)	WP_{IW} (kg m^{-3})	Water Footprint (L kg^{-1} Seed Yield)
Oilseed Brassica species-A			
B. carinata	17.63 ^{A}	1.79 ^{A}	578.8 ^{B}
B. napus	13.95 ^{B}	1.42 ^{B}	892.5 ^{A}
B. juncea	19.15 ^{A}	1.93 ^{A}	503.1 ^{BC}
Crop geometry-B			
S1: 60 × 60	17.88 ^{A}	1.82 ^{A}	630.0 ^{B}
S2: 45 × 45	16.83 ^{A}	1.70 ^{A}	677.7 ^{A}
S3: 45 × 15	16.03 ^{B}	1.63 ^{B}	666.6 ^{A}

Note: (Means followed by different letters in each column for particular set of treatments are significantly different at $p \leq 0.05$ as per Tukey's HSD test).

The similar trend was followed by WP, and the highest WP was recorded under a 60 cm × 60 cm crop geometry, which was significantly higher over the conventional crop geometry (45 cm × 15 cm). The water footprint was also influenced by different crop configurations of crop spacing. Contrary to the WUE and WP, the WPFs remained significantly higher under a conventional crop geometry (666.7 L kg^{-1} of crop economic produce). A broader crop geometry (60 cm × 60 cm) led to low WFPs and efficient use of irrigation water.

4. Discussion

The recent advances like wider plant or row spacing and skip-row arrangements optimizing crop geometry for desired plant stands have been widely accepted for efficient use of available soil and water resources [48,49]. The canopy cover influences the micro-climate within the crop [50] and hence remains instrumental in enhancing crop growth and productivity [51,52]. The crop geometry directly influences light interception, moisture availability, and wind movement, thereby affecting photosynthesis, dry-matter accumulation, crop maturity, and overall productivity. An optimum plant density not only enhances the crop productivity and quality but also reduces pilferages of applied inputs [53]. Two critical inputs like fertilizer and irrigation are efficiently utilized under an optimal plant density in SMI. A higher plant density often reduces light interception and increases resource competition among plants, which adversely affects crop phenological development [54]. With wider spacing, a 33% reduction in the seed requirement of hybrid mustard was recorded, and hence the seed availability for wider coverage can be ensured [55]. Crop-row configuration is a vital agronomic management that has enormous effect on seed yield and the yield components of individual plants [26,56,57]. The earlier studies showed that the optimum row spacing in *B. napus* and other OSB affected seed and oil yield in cultivars [58–60] mainly due to efficient use of available resources (water, light, and soil nutrients). Better adaptability and enhanced productivity in *B. carinata* over canola (*B. napus*) and Indian mustard (*B. juncea*) under adverse agro-climatic conditions have been also reported by many researchers [8,61]. The OSB *B. carinata* has more tolerance for warmer environments over canola and oilseed rape [62]. It also has a greater shattering tolerance than canola and is better adaptable under sub-tropical and tropical conditions under an appropriate geometry [62–64]. That was the probable reason for the higher seed productivity and profitability of *B. carinata* under SMI. The soil organic matter is very crucial for maintaining soil quality mainly because of its multifarious effects on soil properties [65]. The total SOC pools corresponds nearly to three to four times higher over the atmospheric and biospheric C pool, [66,67], and its sequestration potential is mainly governed by the C balance in soil [68]. Gan et al. [69] have highlighted that BMPs for obtaining higher crop productivity and their impact on soil carbon and carbon sequestration for lower C footprint in rapeseed-mustard. SMI resulted in a lower GHGi in *B. napus* and *B. carinata* and improved water-use efficiency [70]. The use of improved crop seeding and row spacing can enhance the canola yield up to 18% [71,72].

Suitable crops and cropping systems have the potential to reduce the amount of atmospheric CO_2 emission, leading to soil organic carbon (SOC) storage and favoring the soil carbon budget [28]. The terrestrial ecosystems approximately buffer 1/3rd of the annual surge of atmospheric CO_2 concentration from GHG emissions presently and are also a net carbon sink of 3 GT/year [73]. Therefore, management of soil C budget through agronomic manipulation with OSB species diversification embodies major potential for climate-change mitigation as well [74]. These strategies could establish agriculture as a net CO_2 sequestration practice from the existing source as a net CO_2 emitter. Lal (2004) [39,75] has also reported that adoption of similar crop-land-management practices can increase soil carbon storage in agroecosystems. Broader crop spacing resulted in a higher CSI (5.07) over conventional spacing. The CSI in *B. carinata* and *B. napus* produced higher yields due to higher plasticity of canopy expansion in these crops. Optimum input use, better recycling of crop residue, and bio-efficiency of specific crops for conversion of all inputs into output ensures a higher CSI [76].

Improved water and other input-use efficiencies were reported highest under optimal planting densities that regulate the association among the individual plant and the population [77–79]. Under water-stressed areas, the hybrid OSB plants absorb water from deeper soil layers due to their specific drought-proofing mechanism [80]. The WUE of applied irrigation water was recorded as a maximum in *B. juncea* (19.15 kg per ha-mm), mainly because of better physio-morphological traits for efficient use of available water and higher seed productivity. The WP of *B. juncea* remained higher, primarily due to the adaptive advantages of Indian mustard (*B. juncea*) over canola (*B. napus*) for efficient water use owing to enhanced crop growth, plant—water relations, and yield [7,81]. Similarly, the lowest water footprint (WFP) was recorded in *B. juncea*, which remained at par with *B. carinata*. Crop geometry under transplanting has also influenced the WUE, WP, and WFP. The broader crop geometry of 60 cm × 60 cm had a greater impact on the WUE (17.88 kg per ha-mm) mainly due to the optimal use of available water [4,51,52]. Hence, the WFT was also influenced by different crop configurations and crop spacings. Hoekstra et al. (2009) [33] also reported lesser WFT as the total volume of freshwater that is used to produce the product was comparatively lower. Contrary to the WUE and WP, the WPFs remained significantly higher under a conventional crop geometry (666.7 L per kg of crop economic produce) due to an exhaustive water-use pattern [82]. While the broader crop geometry (60 cm × 60 cm) led to decreased WFPs and better use of irrigation water, Shekhawat et al. [7], Rathore et al. [35], and Sharma et al. [37] have also reported higher WP for the rapeseed-mustard and suggested the conversion of conventional rain-fed rapeseed-mustard areas into irrigated areas through appropriate irrigation scheduling, which can easily meet the water requirement of the crop.

Efficient energy in agriculture is very crucial in the present context where it is facing the challenges of increasing costs, greenhouse-gas emissions, and greater environmental footprints [38,83,84]. The maximum energy output was recorded from *B carinata* (246,445 MJ ha^{-1}). Hence, energy-efficient crops like *B. carinata* are to be introduced in the existing systems. The high edible oil productivity (1–2 Mg ha^{-1}) and higher energy-conversion efficiency (ratio of energy output to energy input) of OSBs make them a popular choice for cultivation among all oilseed crops [85]. Bielski et al. [84] have also highlighted its vital use as liquid fuel due to the higher energy-efficiency ratio of seeds. The production technology determines the energy demand as energy input and the amount of energy assimilation in biomass (energy output). The efficient energy use, assimilation, and conversion was recorded in *B. carinata* [8,85]. The SMI has been identified and has come up as an effective production technologies for rapeseed-mustard. The declining trend of energy input also resulted in a lower specific energy under a broad crop spacing (60 cm × 60 cm), whereas a narrow, regular crop geometry incurred a higher energy input and consequently a higher specific energy.

5. Conclusions

Declining water-use efficiency and water productivity, increasing GHGs emission and environmental footprints, and poor resource-use efficiency are grave challenges of present-day agriculture.

Modern crop-management strategies might increase productivity but often escalate environmental and economic costs. The farming sector is therefore both a victim as well as a culprit for increasing ecological imbalances, GHGs emissions, etc. For sustainable and climate-smart farming, the environmental implications and sustainability of resource use, the carbon sequestration, increasing WUE, and energy efficiency have become vital. These implications compel to optimize the improved agronomic management with alternate crops and cropping systems for safeguarding ecologies. OSBs are most suitable climate smart crops with known environment-friendly impressions. Further refinement of production technologies for OSB production, including SMI and species diversification, have been reported to result in better resource management, efficient use, and a lesser ecological footprint in terms of water usage and productivity. The present study also emphasized that growing *B. carinata* at wider row spacing improves productivity and profitability with minimum environmental footprints. It can further be introduced under certain identified ecologies with improved cultivation practices for overall environment security.

Author Contributions: Conceptualization, S.S.R., F.M.Z., S.B., H.S. and K.S.; methodology, S.S.R., R.K.S. and P.KU.; software, S.S.R., H.S. and F.M.Z.; validation, K.S., S.B. and P.K.U.; formal analysis, S.S.R.; investigation, S.S.R.; resources, V.K.S., H.S. and S.S.R.; data curation, R.R.; writing—original draft preparation, S.S.R. and F.M.Z.; writing—review and editing, S.S.R. and S.B.; visualization, V.K.S.;

supervision, S.S.R., K.S. and F.M.Z.; project administration, V.K.S.; funding acquisition, V.K.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: All the data statistically analyzed and presented in the manuscript.

Acknowledgments: The authors are highly thankful to the Director of the ICAR-Indian Agricultural Research Institute for extending all support to conduct the field experimentation. The technical staff's cooperation is also duly acknowledged.

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

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