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RICE (*Oryza sativa* L.) SELF-SUFFICIENCY IN MEXICO: IS IT POSSIBLE TO ACHIEVE IT?

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ABSTRACT

Given the significance of rice in the Mexican diet and the country's dependence on imports to meet domestic demand, an examination of the food self-sufficiency index (SSI) for rice, which was 16.9 % in 2021, is required. The goal of this study was to examine the possibility of increasing the SSI to 66 % through crop area and yield increases, as well as to identify the most competitive regions in irrigated and rainfed agriculture under free trade conditions. A spatial equilibrium model that considered yield and potential area was obtained to analyze three scenarios that would place the SSI at 21, 46, and 66 %. The results show that to reach an SSI of 66 %, production would have to rise to 1139.7 thousand Mg, with 144.6 thousand ha of irrigated land and 18.2 thousand ha of rainfed areas, and an average yield of 7.4 and 4.2 Mg ha^{-1}, respectively. The rice-producing states with the highest growth potential would be Nayarit, Campeche, and Michoacán, which have the potential to increase the cultivated area by more than 75 000 ha. Other regions with potential include Veracruz, Colima, and Jalisco. Due to the vulnerability of the domestic market to exogenous international changes resulting from its dependence on imports, it is recommended that the necessary measures be implemented to increase SSI for rice.

Keywords: food self-sufficiency, production, import, yield, area.

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INTRODUCTION

Rice (*Oryza sativa* L.) is the third most consumed cereal in Mexico, after maize and wheat. In 2021, per capita rice consumption was 9.1 kg, with a national production of 257 thousand Mg, a cultivated area of 41 thousand ha, a yield of 6.4 Mg ha^{-1}, and a production value of $1341 million MXN. The main producing states were Campeche, Nayarit, and Michoacán with 28, 20.5, and 13.2 % of total production, respectively (SIAP, 2022a). From 1961 to 2020, rice consumption showed an average annual growth rate (AAGR) of 2.4 %. The North American Free Trade Agreement (NAFTA), which allowed duty-free imports and import quotas, was the most important factor behind the increase in rice consumption, as low rice prices led to an increase in demand.

Food security and supply have been covered by domestic production and imports. From 1961 to 2020, rice imports experienced an average annual growth of 14.4 %, from 0.4 to 1 114.5 thousand Mg. From 1961 to 1985, production had a positive performance; however, from 1985 onwards, a negative trend was observed. From being self-sufficient in the 1961–1990 period, Mexico became a rice importer. During the 2016–2020 period, it had a Food Dependency Index (FDI) of 83.1 % and a Food Self-Sufficiency Index (SSI) of 16.9 %. The FDI and SSI indicate the percentage of total consumption that is supplied by imports and domestic production, respectively, which means that less than one-fifth of consumption was supplied by domestic production in that period (Table 1).

Food self-sufficiency is defined as the degree to which a country can meet its food needs from its own production, as measured by the rate of self-sufficiency (FAO, 1999), or as the ability of a nation to produce the majority of its food requirements (FAO, 2023a). Otero *et al.* (2013) defined it as the ability of a country to provide basic foodstuffs to its population without relying on imports exceeding 20 % of its domestic supply.

The high FDI for rice in Mexico is due to two factors: increasing consumption and decreasing production. The latter experienced an annual decline of -0.2 % during the 1961–2020 period, caused by a decrease in the production area, which showed an annual decline of -1.9 % from 1961 to 2020, while the yield had a positive growth of 1.7 % during the same period. To meet demand in 2021, imports of 1 016.4 thousand

Table 1. Food Dependency Index (FDI) and Food Self-Sufficiency Index (SSI) for palay rice in Mexico (FAO, 2023b).

Period	S ha	R Mg ha^{-1}	P Mg	M Mg	X Mg	C Mg	FDI %	SSI %
1961–1965	137 132	2.3	314 050	6 025	8 825	311 251	1.9	98.1
1966–1970	152 534	2.5	387 537	10 140	6 100	391 577	2.6	97.4
1971–1975	177 945	2.7	486 234	33 188	3 727	515 695	6.4	93.6
1976–1980	147 979	3.2	474 342	38 570	8 855	504 057	7.7	92.3
1981–1985	161 458	3.6	588 213	141 478	0	729 690	19.4	80.6
1986–1990	139 155	3.6	502 737	101 007	57	603 687	16.7	83.3
1991–1995	80 077	4.5	353 819	352 832	114	706 537	49.9	50.1
1996–2000	93 696	4.4	413 505	526 798	2 697	937 606	56.2	43.8
2001–2005	56 714	4.6	259 356	717 251	919	975 688	73.5	26.5
2005–2010	57 537	4.7	267 204	809 213	5 527	1070 890	75.6	24.4
2011–2015	36 050	5.5	200 040	944 118	1 236	1142 922	82.6	17.4
2016–2020	42 839	6.3	268 786	1168 013	30 776	1406 022	83.1	16.9
2021	40 280	6.4	257 041	1016 418	17 364	1256 095	80.9	19.1
$GR_{1961\text{-}20}$ (%)	-67.5	173.0	-11.3	314 889	157.7	324.0	74 190	-79.3
$AAGR_{1961\text{-}20}$ (%)	-1.9	1.7	-0.2	14.4	1.6	2.4	11.6	-2.6

S: harvested area; R: yield; P: production; M: imports; X: exports; C: consumption; GR: growth rate; AAGR: average annual growth rate.

Mg were required, totaling $412 million USD; 84.6 % of imports came from the USA. The highest imports took place in February, April, August, September, and December (10.0, 10.8, 10.9, 10.6, and 10.1 %, respectively), while the months with the highest harvests were June and November, with 16.5 and 30.1 % of national production (SIAP, 2022a).

Which factors explain the fall in rice production? Schwentesius and Gómez-Cruz (1999) identified macroeconomic policy (less support for production due to the withdrawal of the state from its economic functions), trade liberalization, and the difference in price and subsidy policy between the US and Mexico as the factors that caused the decrease in cultivated area. Ireta-Paredes *et al.* (2015) indicated that the causes explaining the loss of competitiveness of the rice producer were the exchange rate, high interest rates, the decrease in subsidies, the lack of integration of the production chain, the increase in production costs, and the decrease in the producer´s price. Another contributing factor was water scarcity in some regions, with 62 % of irrigated rice production established in regions with high water stress (Lerma-Santiago-Pacific, North Pacific, and Balsas) (CEDRSSA, 2015).

During the last decades, Mexico's grain food security policy has taken advantage of the low prices on the international market and has allowed an increasing percentage of consumption to be supplied by imports. Food security is oriented towards the physical and economic accessibility of sufficient, safe, and nutritious food to meet dietary needs (FAO, 2009). To encourage the production of staple crops, the Mexican government has launched the Guarantee Prices Program and the Fertilizer for Well-Being Program, whose target populations include small and medium-sized rice producers.

Should Mexico continue to rely on imports to secure rice consumption? According to the FAO, a country must be able to produce at least 75 % of the food it consumes to provide food security for its population (Curiel, 2013). Otero *et al.* (2013) critiqued the notion of food security that has been central to the discourse of opening up the domestic agricultural sector and showed that food dependency has been stronger in developing countries than in advanced capitalist countries. As an example of this, Mexico adopted neoliberal policies and became dependent on imports of basic foodstuffs, which represents a major risk to food security.

According to SADER (2019), the advantages of food self-sufficiency include protecting the country from changes in international trade and price fluctuations. This generates a supply system that, in addition to securing products, considers production, transformation, trade, and financial and technological services, which saves and generates its own food system, caring for the environment, and improving producers' living conditions.

Ray *et al.* (2013) indicated that to meet global rice demand, production needs to double, implying that the global rice growth rate should be 2.4 %; however, production is actually increasing at a rate of 1 % per year, which is insufficient to meet the projected demand in 2050. Ávila (1982) determined that an improvement in technology was not sufficient to supply the national demand for rice and that it would be necessary to increase the area under cultivation. To achieve food security, Ray *et al.* (2013) concluded that it was better to increase crop yields rather than the area cultivated. To increase yields, Twine (2023) suggested focusing efforts on genetic improvement, seed systems, market intelligence, and strengthening co-ownership.

According to Fathonah and Mashilal (2021), in Pakistan and India, land availability was shown to be an indicator of rice production and self-sufficiency, while in Iran it was increased irrigation efficiency. In China, optimizing self-sufficiency increased capital and relationships between large and profitable enterprises, as well as the creation of policies that included incentives for grain-producing areas, subsidies, agricultural education, and supervision of new farms. Land yields increased in eight African countries, but self-sufficiency will not be achieved by 2025. In Indonesia, food self-sufficiency was promoted through improvements in agricultural infrastructure, reduction of import levels, and revision of government purchase prices, as well as extensification, minimization of post-harvest losses, rice export intensification, and conversion of agricultural land. Of the variables assessed (labor, capital, and area), area has a more significant impact on the growth rate of rice production in Indonesia (Fathonah and Mashilal, 2021).

The objective of this research was to analyze the possibility of achieving an SSI of 66 % through increases in crop area and yield, as well as to identify the most competitive irrigated and rainfed areas for the production of this crop in the context of free trade. The hypothesis is that Mexico can achieve an SSI of 66 %.

MATERIALS AND METHODS

A spatial equilibrium model was used to represent the disaggregated rice market in Mexico. The formulation of the model was based on Takayama and Judge (1971) and Salin *et al.* (2000). Elements of the structure of the Mexican rice market and its relationship with US exports were analyzed. Fuller *et al*. (2003) indicated that the elimination of tariffs would affect producer prices and production in Mexico, and García-Salazar (2015) presented the methodological basis for designing the model and estimating potential production. Other authors, such as García-Salazar *et al*. (2023), used the Food Dependency Index in terms of consumption, production, and exports to determine the necessary growth in area and yield at the national level to decrease imports.

The model considered $i(1,2,...,I = 12)$ palay rice producing regions; $p(1,2,...,P = 13)$ rice milling regions; $j(1,2,...J = 32)$ polished rice consuming regions; $m(1,2,...,M = 5)$ ports and borders of entry for palay rice; $n(1,2,...,N = 6)$ ports and borders of entry for polished rice; and $e(1,2 \text{ and } 3 = E)$ ports of exit of polished rice. The rice-producing regions considered were Nayarit, Campeche, Michoacán, Veracruz, Colima, Tamaulipas, Jalisco, Tabasco, Morelos, Guerrero, Chiapas, and State of Mexico (SIAP, 2022b). The rice-processing regions were Campeche, Colima, Guanajuato, Jalisco, State of Mexico, Michoacán, Morelos, Nayarit, Nuevo León, Puebla, Sinaloa, Tamaulipas, and Veracruz

(INEGI, 2021a). The consumer regions were represented by the 31 Mexican states and Mexico City. The ports and borders of entry for palay rice were Veracruz, Tuxpan, Altamira, Nuevo Progreso, and Nuevo Laredo (SIAP, 2021). The ports and borders of entry for polished rice were Veracruz, Manzanillo, Tijuana, Piedras Negras, Ciudad Juárez, and Nuevo Laredo (SIAP, 2021). The ports of export of polished rice were Veracruz, Manzanillo, and Nuevo Laredo (SIAP, 2021).
The objective function of the model maximizes Net Social Payoff and is equal to the sum of the area under the demand curve minus the area under the supply curve, plus the value of exports, minus the value of imports, minus profit and transportation costs:

$$\begin{aligned} Max\ NSP = &\sum_{j=1}^{J}\left[\lambda_j y_j + \frac{1}{2}\omega_j y_j^2\right] - \sum_{i=1}^{I}\left[v_i x_i + \frac{1}{2}\eta_i x_i^2\right] \\ &+ \sum_{e=1}^{E}[P_e x_e] - \sum_{m=1}^{M}[P_m x_m] - \sum_{n=1}^{N}[P_n x_n] - \sum_{p=1}^{P}[P_P x_p] - \sum_{i=1}^{I}\sum_{p=1}^{P}[C_{ip}^c x_{ip}^c] \\ &- \sum_{p=1}^{P}\sum_{j=1}^{J}[C_{pj}^c x_{pj}^c + C_{pj}^f x_{pj}^f] - \sum_{p=1}^{P}\sum_{e=1}^{E}[C_{pe}^c x_{pe}^c + C_{pe}^f x_{pe}^f] \\ &- \sum_{m=1}^{M}\sum_{p=1}^{P}[C_{mp}^c x_{mp}^c + C_{mp}^f x_{mp}^f] - \sum_{n=1}^{N}\sum_{j=1}^{J}[C_{nj}^c x_{nj}^c + C_{nj}^f x_{nj}^f] \end{aligned} \quad (1)$$

where λ_j and ω_j represent the intercept and slope of the demand function; y_j is the quantity consumed of polished rice in *j*; v_i and η_i are the intercept and slope of the supply function in *i*; x_i is the quantity produced of palay rice in *i*; P_m and x_m are the import price and the imported quantity of palay rice by *m*; P_n and x_n are the import price and the imported quantity of polished rice by *n*; P_e and x_e are the export price and the exported quantity of polished rice by *e*; P_p and x_p are the profit cost and the profited quantity of rice in *p*; C^c_{ip} and x^c_{ip} are the transportation cost and the quantity of palay rice shipped from *i* to *p* by truck; C^c_{pj} and x^c_{pj} are the transportation cost and the quantity shipped from *p* a *j* by truck; C^f_{pj} and x^f_{pj} are the transportation cost and the quantity shipped of *p* to *j* by rail; C^c_{pe} and x^c_{pe} are the transportation cost and the quantity shipped from *p* to *e* by truck; C^f_{pe} and x^c_{mp} are the transportation cost and the quantity shipped from *p* to *e* by rail; C^c_{mp} and x^f_{pe} are the transportation cost and the quantity of palay rice from *m* to *p* shipped by truck; C^f_{mp} and x^f_{mp} are the transportation cost and the quantity of palay rice from *m* to *p* shipped by rail; C^c_{nj} and x^c_{pj} are the transportation cost and the quantity from *n* to *j* shipped by truck; and C^f_{nj} and x^f_{nj} are the transportation cost and the quantity from *n* a *j* shipped by rail.

The shipment of polished rice from *p* and *n* to *j*, by truck and rail, is equal to or greater than the demand for polished rice in *j*:

$$\sum_{p=1}^{P} x_{pj}^{c} + \sum_{p=1}^{P} x_{pj}^{f} + \sum_{n=1}^{N} x_{nj}^{C} + \sum_{n=1}^{N} x_{nj}^{f} \geq y_j \tag{2}$$

The shipment of palay rice from *i* to *p* (discounting δ moisture losses) plus shipments from *m* to *p*, by truck and rail, is equal to or greater than the quantity of rice polished by its processing coefficient *α*:

$$\delta\left[\sum_{i=1}^{I} x_{ip}^{C}\right] + \sum_{m=1}^{M} x_{mp}^{C} + \sum_{m=1}^{M} x_{mp}^{f} \geq X_p\, a_p \tag{3}$$

The shipment of polished rice from *p* to *e*, by truck and rail, is equal to or greater than the exported quantity of polished rice by *e*:

$$\sum_{p=1}^{P} x_{pe}^{C} + \sum_{p=1}^{P} x_{pe}^{f} \geq X_e \tag{4}$$

The shipment of polished rice from *p* to *e* and *j*, by truck and rail, is equal to or less than the quantity of milled rice in *p*:

$$\sum_{j=1}^{J} x_{pj}^{c} + \sum_{j=1}^{J} x_{pj}^{f} + \sum_{e=1}^{E} x_{pe}^{C} + \sum_{e=1}^{E} x_{pe}^{f} \leq x_p \tag{5}$$

The shipment of palay rice from *i* to *p*, by truck, is equal to or less than the quantity of palay rice produced in *i*.

$$\sum_{p=1}^{P} x_{ip}^{C} \leq x_i \tag{6}$$

The shipment of polished rice from *n* to *j* is equal to or less than the quantity of polished rice imported by *n*.

$$\sum_{j=1}^{J} x_{nj}^{C} + \sum_{j=1}^{J} x_{nj}^{f} \leq x_n \tag{7}$$

The shipment of palay rice from *m* to *p*, by truck and rail, is equal to or less than the imported quantity of palay rice by *m*.

$$\sum_{p=1}^{P} x_{mp}^{C} + \sum_{p=1}^{P} x_{mp}^{f} \leq x_m \tag{8}$$

The following equation sets the limit for imports of palay rice:

$$\mu x_m \geq \sum_{m=1}^{M} x_m \tag{9}$$

where μ represents the SSI (%).

Finally, the non-negativity conditions are represented as follows:

$$y_j, x_i, \ldots . x_{nj}^{f}, x_{pe}^{f}, \geq 0 \tag{10}$$

A baseline model was validated for the year 2020. The endogenous variables considered were: production, consumption, imports of palay and polished rice, exports of polished rice, quantity of rice milled, and trade flows. To validate the model, the observed values (in terms of palay rice) of production, consumption, imports, irrigated and rainfed harvested area, and irrigated and rainfed yields were compared using the values estimated by the base model, which showed differences, in absolute terms, of less than 10 %.

To determine the most competitive areas, three scenarios were obtained: 1) changes in RR (irrigated yield), RT (rainfed yield), and ST (rainfed harvested area), keeping SR (irrigated harvested area) constant; 2) changes in RR, RT, and SR, keeping ST constant; and 3) changes in RR, RT, SR, and ST. In each scenario, increases in area and yield were made to set the SSI at 21, 46, and 66 %. Potential yield and area to produce rice were taken as upper limits. The most competitive regions would be those where production increases when the SSI increases.

To develop the scenarios, the following constraints were added to the model:

$$x_i = \sum_{i=1}^{I} SR_i * RR_i + \sum_{i=1}^{I} ST_i * RT_i \tag{11}$$

$$\sum_{i=1}^{I} SR_i \geq \sum_{i=1}^{I} SRO_i \tag{12}$$

$$\sum_{i=1}^{I} SR_i \leq \sum_{i=1}^{I} SRP_i \quad (13)$$

$$\sum_{i=1}^{I} ST_i \geq \sum_{i=1}^{I} STO_i \quad (14)$$

$$\sum_{i=1}^{I} ST_i \leq \sum_{i=1}^{I} STP_i \quad (15)$$

$$\sum_{i=1}^{I} RR_i \geq \sum_{i=1}^{I} RRO_i \quad (16)$$

$$\sum_{i=1}^{I} RR_i \leq \sum_{i=1}^{I} RRP_i \quad (17)$$

$$\sum_{i=1}^{I} RT_i \geq \sum_{i=1}^{I} RTO_i \quad (18)$$

$$\sum_{i=1}^{I} RT_i \leq \sum_{i=1}^{I} RTP_i \quad (19)$$

where for region *i*: SR_i, ST_i, RR_i, and RRT_i are the irrigated and rainfed area and yield; SRO_i, STO_i, RRO_i and RTO_i are the observed irrigated and rainfed area and yield; and SRP_i, STP_i, RRP_i and RRP_i are the potential irrigated and rainfed area and yield.

Equation 11 indicates that rice production is equal to the production obtained under irrigation and rainfed conditions. Equations 12 to 15 set lower and upper limits to the rice area; the lower limit corresponds to the area observed in the year of analysis and the upper limit to the potential area. Similarly, equations 16 to 19 set lower and upper limits to the rice yield.
The data used is for the year 2020. The supply functions for palay rice and demand for polished rice by region were calculated using price elasticities of supply and demand, quantities produced and consumed, and producer and consumer prices (García-Salazar, 2015). Elasticities were taken from Vázquez-Alvarado and Martínez-Damián

(2015). The amount of palay rice produced by region was obtained from SIAP (2022b). A 15 % loss due to moisture was taken into account. To obtain the amount of rice consumed by region, the method proposed by García-Salazar (2015) was used. First, the Apparent National Consumption (CNA) of palay rice was obtained by adding imports to production and deducting exports. The CNA of polished rice resulted from multiplying the CNA of palay rice by its transformation coefficient plus the imported minus the exported quantities of polished rice. Regional consumption was obtained by multiplying the CNA of polished rice by a weight representing the population share of each region j (INEGI, 2021b).

The producer price was calculated by adding the import price of palay rice plus the cost of transportation from the port to the mill, minus the cost of transportation from the producing region to the mill, and minus the cost of drying. The consumer price was obtained by adding the import price of polished rice and the cost of transportation from the port to the consumption area. Import prices of palay and polished rice and export prices of polished rice by port or border were calculated by dividing their value by the quantity multiplied by the exchange rate in 2020. Rice beneficiation quantity, beneficiation cost, and drying cost were obtained from Mendoza-Mondragón (2022), while palay rice imports and polished rice imports and exports were obtained from SIAP (2021).

The cost of transportation by train was estimated with a distance matrix and the average tariff, including a fixed factor and a variable factor for the transportation of palay and polished rice (ARTF, 2020). To estimate the transportation cost per truck, a distance matrix was used; quotes were obtained using the GlobalMap Software trial version (GlobalMap, 2021) for transportation type T3-S2 with a load capacity of 30 Mg, adding 35 % to the cost for the carrier's profit.

Area, yield, and production by cycle (spring-summer and autumn-winter) and water regime were obtained from SIAP (2022b). Import, export, production, consumption, and processing ratio were obtained from FAO (2023b). The exchange rate was taken from Gobierno de México (2021) and the potential state area by water regime from SIAP (2023). The method proposed by García-Salazar and Skaggs (2015) was used to determine the potential yield. Potential yields by state were calculated using information on observed municipal yields. The potential yield in a district was assumed to be equal to the highest yield observed in the leading municipality (the one with the highest yield).

RESULTS AND DISCUSSION

The validation of the model (Table 2) consisted of comparing the estimated values of the rice market variables with the observed values in 2020. The acceptance criterion for the base model is that the differences between observed and estimated should be less than ± 10 %. In this case, the estimated model underestimates production in Guerrero and the State of Mexico with 0.2 and 0.8 % and overestimates production in the State of

Jalisco, rainfed yield, and national consumption with 0.1, 0.1, and 0.4 %. The differences were less than 1 % for all the variables analyzed (Table 2); therefore, the model can be used to run scenarios. The base model estimated total production at 295.3 thousand Mg, of which 83.4 % was obtained in 35.1 thousand ha harvested under irrigation with a yield of 7 Mg ha^{-1} and the rest in 12.4 thousand ha under rainfed conditions with a yield of 3.9 Mg ha^{-1}. Domestic and import consumption reached values of 1.4 and 1.2 million Mg, with an SSI of 16 %.

The results of the scenarios (Table 3) show that in order to increase production and achieve an SSI of 21 %, the following options are available: a) 27.6 thousand ha in rainfed conditions, with a yield of 4.5 Mg ha^{-1}, and 35.1 thousand ha in irrigated conditions, with a yield of 7.5 Mg ha^{-1}; b) 45.5 thousand ha in irrigated conditions, with a yield of 7.3 Mg ha^{-1}, and 12.5 thousand ha in rainfed conditions, with a yield of 4.6 Mg ha^{-1}; and c) allocate 44.5 thousand ha in irrigation and 12.5 thousand ha in rainfed conditions with yields of 7.5 and 4.4 Mg ha^{-1}. The above indicators would put production at 387.1 thousand Mg and imports would decrease to 1 135.4 thousand Mg. To increase production and achieve an SSI of 46 %, the following alternatives are available: a) harvest 131.3 thousand ha of rainfed land with a yield of 4.1 Mg ha^{-1} and 35.1 thousand ha of irrigated land with a yield of 7.4 Mg ha^{-1}; b) harvest 100.9 thousand

Table 2. Validation of the spatial equilibrium model of the rice market in Mexico for year 2020.

Region	Situation observed	Base model	Difference	Difference (%)
National production (Mg)†	295 338	295 336	-2	0.0
Campeche	72 230	72 215	-15	0.0
Colima	19 006	19 010	4	0.0
Chiapas	673	672	0	0.0
Guerrero	2362	2358	-4	-0.2
Jalisco	17 130	17 143	13	0.1
Mexico	334	331	-3	-0.8
Michoacán	30 056	30 047	-9	0.0
Morelos	8839	8837	-2	0.0
Nayarit	88 828	88 825	-3	0.0
Tabasco	7421	7421	0	0.0
Tamaulipas	14 040	14 040	0	0.0
Veracruz	34 419	34 435	16	0.0
Irrigated area (ha)	35 104	35 104	0	0.0
Rainfed area (ha)	12 449	12 450	1	0.0
Irrigated yield (Mg ha^{-1})	7.0	7.0	0	0.0
Rainfed yield (Mg ha^{-1})	3.9	4.0	0	0.1
National consumption (Mg)†	1 433 884	1 434 639	756	0.1
Imports (Mg)¶	1 209 267	1 213 507	4240	0.4

†Palay rice production in the field; for comparison with palay rice imports, it is necessary to deduct the losses due to drying. ¶Consumption and imports consider palay rice plus clean rice (in terms of palay rice).

Table 3. Increasement of the Food Self-Sufficiency Index (SSI) of palay rice in Mexico through changes in yield and cultivated area.

Region	Model Basis	Scenarios			Change (%) §		
		E1	E2	E3	E1	E2	E3
			SSI of 21 %				
Production (Mg)†	295 336	387 070	387 063	387 063	31.1	31.1	31.1
Irrigated area (ha)	35 104	35 104	45 451	44 535	0.0	29.5	26.9
Rainfed area (ha)	12 450	27 638	12 450	12 450	122.0	0.0	0.0
Irrigation yield (Mg ha^{-1})	7.0	7.5	7.2	7.5	6.6	3.4	6.3
Rainfed yield (Mg ha^{-1})	4.0	4.5	4.6	4.4	14.2	16.9	11.6
National consumption (Mg)¶	1 434 639	1 434 637	1 434 638	1 434 638	0.0	0.0	0.0
Domestic imports (Mg)¶	1 213 507	1 135 363	1 135 364	1 135 364	-6.4	-6.4	-6.4
			SSI of 46 %				
Production (Mg)†	295 336	804 214	804 214	804 214	172.3	172.3	172.3
Irrigated area (ha)	35 104	35 104	100 990	69 568	0.0	187.7	98.2
Rainfed area (ha)	12 450	131 266	12 450	18 179	954.3	0.0	46.0
Irrigation yield (Mg ha^{-1})	7.0	7.4	7.4	7.3	6.1	5.4	4.6
Rainfed yield (Mg ha^{-1})	4.0	4.1	4.6	4.6	4.7	16.8	15.2
National consumption (Mg)¶	1 434 639	1 434 606	1 434 632	1 434 632	0.0	0.0	0.0
Domestic imports (Mg) ¶	1 213 507	780 558	780 590	780 590	-35.7	-35.7	-35.7
			SSI of 66 %				
Production (Mg)†	295 336	1 139 742	1 139 736	1 139 744	285.9	285.9	285.9
Irrigated area (ha)	35 104	35 104	142 168	144 642	0.0	305.0	312.0
Rainfed area (ha)	12 450	182126	12 450	18 179	1362.9	0.0	46.0
Irrigation yield (Mg ha^{-1})	7.0	7.4	7.6	7.3	6.1	8.6	4.8
Rainfed yield (Mg ha^{-1})	4.0	4.9	4.6	4.2	23.7	16.9	7.2
National consumption (Mg)¶	1 434 639	1 434 476	1 434 604	1 434 632	0.0	0.0	0.0
Domestic imports (Mg)¶	1 213 507	495 083	495 217	495 235	-59.2	-59.2	-59.2

†Palay rice production in the field; for comparison with Palay rice imports, it is necessary to deduct the losses due to drying. ¶Consumption and imports consider palay rice plus clean rice. §Change in % of the outcome of each scenario compared to the baseline model outcome.

ha of irrigated land with a yield of 7.4 Mg ha^{-1} and 12.5 thousand ha of rainfed land with a yield of 4.6 Mg ha^{-1}; and c) harvest 69.6 thousand ha of irrigated land and 18.2 rainfed with yields of 7.3 and 4.6 Mg ha^{-1}. The above indicators put production at 804.2 thousand Mg and imports at 780.6 thousand Mg.

Increasing rice production and achieving an SSI of 66 % requires: a) harvesting 182.1 thousand ha in rainfed conditions, with a yield of 4.9 Mg ha^{-1}, and 35.1 thousand ha in irrigated conditions, with a yield of 7.4 Mg ha^{-1}; b) harvesting 142.2 thousand ha in irrigated conditions, with a yield of 7.6 Mg ha^{-1}, and 12.5 thousand ha in rainfed conditions, with a yield of 4.6 Mg ha^{-1}; and c) harvesting 144.6 thousand ha in irrigation and 18.2 in rainfed conditions, with yields of 7.3 and 4.2 Mg ha^{-1}. The above indicators would place production at 1 139.7 thousand Mg and imports at 495.2 thousand Mg, thus reaching food self-sufficiency with an SSI of 66 %.

Regarding the area and yield required at the state level to increase the SSI of rice to 66 % (Table 4), the states of Nayarit, Campeche, Michoacán, Veracruz, and Jalisco would contribute 119.7 thousand ha, representing 82.7 % of the area harvested under irrigation, with Nayarit being the most competitive state in irrigation with 39.4 thousand ha. Campeche and Veracruz would contribute 14.7 thousand ha, representing 80.1 % of the area harvested under rainfed conditions. Campeche is the most competitive rainfed state and could allocate 123 000 ha to rice cultivation.

The national yield on irrigated harvested area would increase by 4.8 % (from 7 to 7.3 Mg ha^{-1}). The states with the highest increases were Campeche, Colima, and Jalisco with 17, 8.7, and 8.5 %, respectively. For rainfed harvested areas, yields would increase by 7.2 % (from 4 to 4.2 Mg ha^{-1}), with Veracruz, Colima, and Campeche showing increases of 27.3, 9.4, and 5.5 %, respectively.

The results indicate that it is possible to achieve rice self-sufficiency in Mexico. This is possible through the use of technological innovations, mainly the genetic improvement of seeds aimed at increasing production yields. García-Angulo *et al.* (2011) indicated that the Silverio variety can be grown rainfed or rainfed with relief irrigation in the humid tropics of the southeast (Veracruz, Oaxaca, Tabasco, Campeche, and Chiapas), in the sub-humid tropics of the northeast (Tamaulipas), and under irrigation in the dry tropics (Nayarit, Jalisco, Colima, and Michoacán). The average yield potential of this variety is 6 Mg ha^{-1} in rainfed conditions, 7 Mg ha^{-1} in rainfed conditions with relief irrigation, and 8 Mg ha^{-1} under irrigation.

Álvarez-Hernández *et al.* (2018) found that long and thin grain rice lines were adapted to the Michoacán production area with yields between 8 and 8.5 Mg ha^{-1} under irrigated conditions. Hernández-Aragón *et al*. (2019) demonstrated that the Pacific FL 15 and Gulf FL 16 rice varieties were stable in the ecosystems of both coasts of Mexico; they observed high yield potential in the Huasteca region, Morelos, Michoacán, Jalisco, and Nayarit with 9.8, 10.8, 12.02, 7.11, and 11.4 Mg ha^{-1} under irrigated conditions, in Colima with 8.65 Mg ha^{-1} under rainfed conditions with precarious irrigation, and in Tabasco with 4.05 Mg ha^{-1} under rainfed conditions. Barrios-Gómez *et al.* (2018) evaluated the Morelos A-2016 variety (Morelos coarse grain type) under transplanting, direct sowing, and irrigation conditions, obtaining yields of 12 to 13.5 Mg ha^{-1} at sites in Morelos, Mexico, Michoacán, Jalisco, and Guerrero. The above yields are similar to the potential yield established for each of the states in this research.

Ávila *et al.* (1982) indicated that, in order to increase production, it is not enough to increase yields, but it is necessary to increase the area. It has been reported that Mexico has 1.6 million ha of high productive potential and 2.9 million ha of medium productive potential for rice production (INIFAP, 2012). The greatest concentration of high productive potential is distributed over the Pacific Coastal Plain, the Sierra Madre del Sur, the Central American Cordillera, the Northern and Southern Coastal Plains of the Gulf of Mexico, the Eastern Neovolcanic Axis, and the Yucatan Peninsula. Mexico has 10.7 million ha of productive potential in the spring-summer cycle and 10.2 million ha in autumn-winter (SAGARPA, 2017). Turrent-Fernández *et al.* (2004)

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Table 4. Area and yield required to increase the Food Self-Sufficiency Index (SSI) of rice by 66 % in Mexico.

Region	Model Basis	E3	Change	Model Basis	E3	Change
	Irrigated rice production (Mg)			Rainfed rice production (Mg)		
Campeche	47 485	236 437	188 952	24 730	49 015	24 285
Colima	9998	59 983	49 985	9011	9863	853
Chiapas	0	1911	1911	672	711	38
Guerrero	2131	8724	6593	227	234	6
Jalisco	17 143	61 437	44 294	0	0	0
Mexico	331	1248	917	0	0	0
Michoacán	30 047	112 435	82 388	0	0	0
Morelos	8837	33 132	24 295	0	0	0
Nayarit	83 771	342 353	258 582	5054	5054	0
Tabasco	7421	30 100	22 678	0	0	0
Tamaulipas	14 040	54 652	40 612	0	0	0
Veracruz	24 948	120 378	95 430	9485	12 079	2594
Total	246 153	1 062 789	816 636	49 179	76 955	27 776
	Irrigated area (ha)			Rainfed area (ha)		
Campeche	8145	34 658	26 513	6525	12 254	5729
Colima	1610	8886	7276	1774	1774	0
Chiapas	0	305	305	382	382	0
Guerrero	266	1089	823	118	118	0
Jalisco	2971	9814	6843	0	0	0
Mexico	52	120	68	0	0	0
Michoacán	3502	13 104	9602	0	0	0
Morelos	853	3198	2345	0	0	0
Nayarit	12 770	52 188	39 418	1337	1337	0
Tabasco	930	3772	2842	0	0	0
Tamaulipas	1950	7591	5641	0	0	0
Veracruz	2055	9916	7861	2314	2314	1
Total	35 104	144 642	109 538	12 449	18 179	5730
	Irrigated yield (Mg ha^{-1})			Rainfed yield (Mg ha^{-1})		
Campeche	5.8	6.8	1.00	3.8	4	0.20
Colima	6.2	6.8	0.60	5.1	5.6	0.50
Chiapas	5.8	6.3	0.50	1.8	1.9	0.10
Guerrero	8	8	0.00	1.9	2	0.10
Jalisco	5.8	6.3	0.50	0	0	0.00
Mexico	6.4	10.4	4.00	0	0	0.00
Michoacán	8.6	8.6	0.00	0	0	0.00
Morelos	10.4	10.4	0.00	0	0	0.00
Nayarit	6.6	6.6	0.00	3.8	3.8	0.00
Tabasco	8	8	0.00	0	0	0.00
Tamaulipas	7.2	7.2	0.00	0	0	0.00
Veracruz	12.1	12.1	0.00	4.1	5.2	1.10
Total	7	7.3	0.30	4	4.2	0.20

noted that south-southeast Mexico has abundant freshwater and arable land that remains idle in the autumn-winter cycle, making investment in hydro-agricultural infrastructure a very high priority.

Aguirre-Álvarez (2009) indicates that the Huasteca plain has hydraulic infrastructure to irrigate 143 000 ha with yields of 8 Mg ha^{-1}. Moctezuma-López *et al.* (2021) identified 257.9 thousand ha with medium and high production potential and indicated that Tabasco could contribute 662.3 thousand Mg of rice if 105 thousand ha with high production potential were planted. This study shows that, although Tabasco has good land and water conditions, it does not significantly increase its cultivated area (22 678 ha) because other factors such as proximity to markets, transportation costs, and yields were considered. In the case of Tamaulipas, the increase in irrigated harvested area is 40.6 thousand ha.

Mexico has the potential to achieve food self-sufficiency. Torres and Rojas (2018) estimated that a harvested area of 184.1 thousand ha with a yield of 5.4 Mg ha^{-1} is required to meet rice demand in 2030. This study suggests increases in yields and irrigated area, which will require investment in hydro-agricultural infrastructure, thus improving water productivity. According to Carracelas *et al.* (2021), by optimizing water use, this resource can be redirected to plant a larger area of rice or other crops, reducing the cost of irrigation and labor, as well as the crop’s water footprint and environmental impact. These authors state that water productivity can be improved through: a) irrigation systems with controlled deficit, systematization of irrigation in the field, reduction of the irrigation period, use of polytubes, construction of taipans or parapets in advance, carrying out field work in advance (summer), reduction of losses through surface runoff, and percolation; b) the use of short-cycle varieties or those with a structure that allows better use of the available water; and c) the improvement and systematization of the water conduction systems in the field.

In a market economy, the producer will choose to plant rice based on profitability, which is equal to the income the producer receives from the sale of his product minus the cost of production, which the producer will pay for the inputs used in the production process; thus, government policies, market imperfections, and some macroeconomic policies will all have an impact on profitability. The Federal Government’s Guarantee Price Policy, in effect since 2019, has a positive effect on producer income, and the Fertilizer for Welfare Program has a positive effect on profitability by lowering the acquisition cost of fertilizer, one of the primary inputs used in production. Market imperfections also have an impact on profitability. A local monopsony (the only industry buying palay rice in the region) may have a negative impact on the producer’s income because the firm pays a low price for the raw material; similarly, a local monopoly (the only firm selling inputs in the region) may have a negative impact on production costs because it sells inputs at high prices.

Some macroeconomic policies would also have an impact on profitability; for example, a high interest rate would raise the cost of capital, thereby increasing the cost of production, as would an increase in the minimum wage paid to the producer’s hired labor. The exchange rate policy would also have an impact on profitability; the recent peso appreciation will reduce costs by lowering the price of imported inputs, but it may have a negative impact on income if the price of palay rice falls due to a drop in the international price of the rice.

Mexico must implement the necessary policies to ensure high profitability in rice production and support the goal of achieving self-sufficiency, which is justified by: a) the high per capita consumption of rice and the inclusion of the cereal in the basic food basket of Mexicans, where 76. 5 % of the population has an income below the poverty line (CONEVAL, 2020); b) the high expenditure in foreign currency to import rice, which in 2021 was 412 million (SIAP, 2022a); c) the high vulnerability of the Mexican rice market to exogenous international changes (Covid-19, Russia-Ukraine war and fertilizer shortages); and d) the risk of probable increases in the international price of rice that would affect the low-income population, which spends more than 40 % of its income on food.

CONCLUSIONS

Through the formulation of a spatial equilibrium model, we can conclude that Mexico has the potential to increase rice self-sufficiency. An increase in irrigated area of 109.5 thousand ha and rainfed area of 5.7 thousand ha, as well as increases in yields of 4.8 and 7.2 %, respectively, would raise the rice food self-sufficiency index to 66 %. The model's economic and logistical conditions indicate that the most competitive regions are Nayarit, Campeche, and Michoacán, which have the potential to increase the area by more than 75,000 ha; other entities with potential include Veracruz, Colima, and Jalisco.

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