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Full Length Research Paper

Opportunities in utilization of agricultural residues in bio-composite production: Corn stalk (*Zea mays indurata* Sturt) and oak wood (*Quercus Robur* L.) fiber in medium density fiberboard

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In this paper, corn stalk as an agricultural residue was mixed with oak wood fiber to produce medium density fiberboards (MDF). Urea formaldehyde resin was used as binder. Hygroscopic and mechanical properties were evaluated according to the commercial standards in MDF production. Partial substitution of wood fiber with corn stalks fiber negatively affected all board properties. However, the mechanical properties fulfill the minimum requirements of the relevant standards such as TS-EN 310, 1999 and TS-EN 319, 1999. In some cases, they exceeded the standards, even with partial blending of corn stalk fibers.

Key words: Corn stalks, *Quercus robur*, medium density fiberboard, physical and mechanical properties.

INTRODUCTION

The demand for forest products is increasing with increase in population. In order to meet this demand, more trees need to be harvested and removed from the forest. This is raising the pressure on the natural resources. This pressure leads to searching of new sources for utilization by forest product industries. Agricultural residues are abundant and renewable annually. As a result, agricultural residues became excellent alternative sources to replace wood and wood fiber. Moreover, it is an environmentally friendly practice due to disposal methods. In general, agricultural residue is destroyed by fire.

Wood, as a lignocellulosic material, has been used for fuel, pulp, paper and composites production for centuries to meet demand (Fengel and Wegener, 1989; Youngquist et al., 1994). As a result, wood consumption increases everyday. This consumption is going to be 4.66 billion m^3 in the year 2010 (Kozlowski and Helwig, 1998). This result points out the deficiency of forest resources and the impact of increased wood consumption. Therefore, the lack of raw material is forcing the blending or replacement of wood fiber with other lignocellulosic materials to obtain products. One of the examples was blending agricultural residues with wood fiber to produce medium density fiberboards (MDF).

Agricultural residues generated in Turkey are almost 54.5 million m^3 annually (Konukcu, 2001). Among these productions, a remarkable amount (4.2 million m^3) is corn stalks and this is available for industrial use (Akgül et al., 2005; Fidan et al., 2008). There are many scientists that examined the replacement of wood with other agricultural residues. Among these residues, kiwi prunings, cotton carpel and stalks, sunflower stalks and hazelnut husk were utilized in the production of composite panels (Akgül et al., 2005; Nemli et al., 2003; Alma et al., 2005; Güler and Özen, 2004; Bektaş et al., 2005; Çopur et al., 2007). All findings from these researches showed that these agricultural residues could be used in industries without

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Abbreviations: MDF, Medium density fiberboards; **MOR,** bending strength; **MOE,** modulus of elasticity; **IB,** internal bonding strength.

Table 1. The properties of urea-formaldehyde (UF) resin.

Property	Unit	Value
Solid content	%	55 ± 1
Density (20℃)	g cm^{-3}	1.227
Viscosity (20℃)	Cps	185
Flowing time (20℃)	S	25-40
Free formaldehyde (max)	%	0.7
Gel time (100℃) (10% NH_3SO_4)	s	40 – 60
Shelf time (20℃)	day	45
pH	-	7.5 – 8.5

Table 2. Production parameters of MDF.

Parameter	Value
Press temperature (℃)	150
Pressing time (min)	5
Press pressure (N mm^{-2})	2.4 - 2.6
Thickness (mm)	10
Dimensions (mm)	480 × 480
Specific gravity (g cm^{-3})	0.7 - 0.8
Number of board for each type	2

any significant quality loss.

Chemical content of corn stalk contains cellulose (35 - 50%), lignin (5 - 34%) and pentosan around 20 - 41% (Han and Rowell, 1997). The morphological properties of corn stalks have fiber length (1.32 mm), fiber width (24.3 µm), lumen width (24.3 µm) and cell wall thickness (6.8 µm) (Usta et al., 1990).

In recent years, many wood composites are produced and new plants are planned worldwide to meet the demand. Among these wood composites, a MDF is frequently used in place of many other wood products. When it is used in place of other products, there are several requirements that need to be fulfilled. In addition to that, during the production, if virgin wood fiber is mixed with agricultural residues, mechanical properties are expected to change as good as that of the board made from virgin wood fiber. Although, corn stalks have been studied in the production of paper, there is limited study in the utilization of fiberboard production. Therefore, the aim of this study is to investigate the potential utilization of corn stalks in medium density fiberboard production as supplement and to alleviate the shortage of raw materials in forest industry.

MATERIALS AND METHODS

Wood (*Quercus robur* L.) and corn (*Zea mays indurata* Sturt.) stalks were the raw materials utilized in board production. Corn stalks were collected from the field right after harvesting and the obtained materials were cleaned from dirt and dust by washing.

Fibers from both oak chips and corn stalks were generated with a pressurized disc refiner at feed pressure of 10 and 40 psi, air dried and bagged for panel manufacturing in Divapan Inc. (Turkey). All materials were dried at 100 - 110℃ until they reached 3% moisture content before panel production. Panels were manufactured at densities of 0.70 and 0.80 g cm^{-3} with 11% resin using urea formaldehyde. Based on the oven dry weight of the materials, the panels were prepared at the thickness of 10 mm. In addition, wax (1%) was used in panel production as water repellent. The properties of the urea-formaldehyde used in this study are given in Table 1. As a hardener, 1% of ammonium chloride (solid content, 33%) solution was added in all board production. Materials were mixed for 3 min to accomplish a homogenized resin distribution. Medium density fiberboard production parameters are summarized in Table 2. The panels comprised furnishings with varying degrees of corn stalks and oak wood fiber mixtures (Table 3).

Table 3. The experimental design.

Board type	Corn stalk fiber (C)	Oak fiber (Q)
A	100	0
B	75	25
C	50	50
D	25	75
E	0	100

Panels were pressed for 5 min at 150℃ and conditioned at 65 ± 5% RH and 20 ± 1℃ in accordance with the TS 642-ISO 554 (1997). Subsequently, physical and mechanical properties were evaluated. Test specimens were cut from the fiberboards according to TS-EN 326-1 (1999) and the samples were kept in the conditioning room for 24 h. The water absorption and thickness swelling of the materials were determined according to TS-EN 317 (1999). The specimens were also tested for bending strength and modulus of elasticity (TS-EN 310, 1999), internal bonding strength (TS-EN 319, 1999) and Janka hardness (ASTM D 1037-78). The data was statistically analyzed by using the analysis of variance (ANOVA) and Duncan mean separation tests.

RESULTS AND DISCUSSION

The result from the present study points out the deficiency of forest resources and the impact of increased wood consumption. Therefore, lack of raw material is forcing the blending or replacement of wood fiber with other lignocellulosic materials to obtain products. One of the examples was blending agricultural residues with wood fiber to produce MDF.

The results of ANOVA and Duncan mean separation tests for the thickness swelling and water absorption of fiberboards produced are given in Table 4. The mean thickness swelling percentage using mixture of corn stalks and oak wood fibers significantly differed in terms of water immersion time ($p < 0.001$). Swelling percentage was increased with soaking time from 2 to 24 h for all panel types. Results indicated that the density of the panels had effect on the thickness swelling for most of the produced panels. On the other hand, panel type B and C for 2 h and panel type A, B and C for 24 h resulted in an insignificant thickness swelling, even with the varying density of the panels. These could be due to corn

Table 4. Thickness swelling and water absorption test results of MDF.

Physical property	Board type	Density	Soaking time (min)	Mean (%)[a]	Std. deviation	Std. error	X_{Min}[b]	X_{Max}[c]	p[d]
Thickness swelling (TS)	A	0. 7	2	12. 23[p]	0. 833	0. 264	11. 08	13. 65	*
		0. 8	2	10. 63[s]	0. 785	0. 248	9. 65	12. 67	*
	B	0. 7	2	10. 62[p]	0. 933	0. 295	8. 93	11. 96	NS
		0. 8	2	10. 13[p]	0. 621	0. 197	9. 06	10. 87	NS
	C	0. 7	2	10. 20[p]	0. 539	0. 171	9. 01	10. 92	NS
		0. 8	2	9. 82[p]	0. 969	0. 306	8. 36	10. 94	NS
	D	0. 7	2	8. 68[p]	0. 366	0. 116	8. 11	9. 24	*
		0. 8	2	6. 41[s]	0. 454	0. 144	5. 67	7. 22	*
	E	0. 7	2	8. 50[p]	1. 436	0. 454	5. 35	9. 85	*
		0. 8	2	5. 30[s]	0. 657	0. 208	4. 14	6. 65	*
	A	0. 7	24	17. 84[x]	0. 889	0. 281	15. 88	18. 88	NS
		0. 8	24	17. 89[x]	0. 640	0. 203	17. 07	18. 89	NS
	B	0. 7	24	15. 87[x]	0. 633	0. 200	14. 92	16. 83	NS
		0. 8	24	16. 70[x]	1. 354	0. 428	14. 25	19. 81	NS
	C	0. 7	24	15. 31[x]	1. 316	0. 416	13. 34	17. 88	NS
		0. 8	24	14. 24[x]	0. 947	0. 299	13. 12	16. 42	NS
	D	0. 7	24	14. 39[x]	1. 033	0. 327	11. 78	15. 6	*
		0. 8	24	11. 47[y]	0. 795	0. 251	10. 24	13	*
	E	0. 7	24	13. 39[x]	0. 565	0. 179	12. 26	14. 18	*
		0. 8	24	10. 85[y]	0. 833	0. 263	9. 85	12. 63	*
Water absorption (WA)	A	0. 7	2	40. 70[p]	2. 413	0. 763	36. 06	42. 76	*
		0. 8	2	27. 43[s]	1. 004	0. 317	25. 32	28. 87	*
	B	0. 7	2	38. 13[p]	1. 122	0. 355	36. 4	39. 72	*
		0. 8	2	26. 05[s]	1. 680	0. 531	23. 01	28	*
	C	0. 7	2	31. 82[p]	0. 906	0. 287	30. 16	33. 14	*
		0. 8	2	21. 40[s]	4. 977	1. 574	14. 17	28. 84	*
	D	0. 7	2	29. 37[p]	1. 892	0. 598	26. 8	31. 6	*
		0. 8	2	17. 33[s]	0. 753	0. 238	16. 28	18. 26	*
	E	0. 7	2	24. 08[p]	1. 422	0. 450	21. 69	27. 27	*
		0. 8	2	13. 49[s]	0. 414	0. 131	13. 1	14. 32	*
	A	0. 7	24	61. 62[x]	1. 558	0. 493	58. 68	64. 47	*
		0. 8	24	46. 51[y]	1. 893	0. 599	44. 53	49. 76	*
	B	0. 7	24	59. 25[x]	1. 676	0. 530	56. 36	62. 17	*
		0. 8	24	39. 95[y]	1. 217	0. 385	38. 65	42. 42	*
	C	0. 7	24	59. 00[x]	2. 673	0. 845	56. 03	62. 98	*
		0. 8	24	39. 33[y]	0. 832	0. 263	37. 98	40. 34	*
	D	0. 7	24	52. 82[x]	1. 516	0. 479	50. 82	56. 61	*
		0. 8	24	34. 04[y]	1. 194	0. 378	32. 45	35. 78	*
	E	0. 7	24	46. 47[x]	1. 809	0. 572	44. 54	49. 4	*
		0. 8	24	32. 47[y]	1. 936	0. 612	29. 37	35. 92	*

[a]Mean values are the average of 20 specimens. [b]maximum value; [c]minimum value; [d]significance level; [*]significant at 0.001, NS; non significant for ANOVA; [p,s,x,y] values having the same letter are not significantly different (Duncan test).

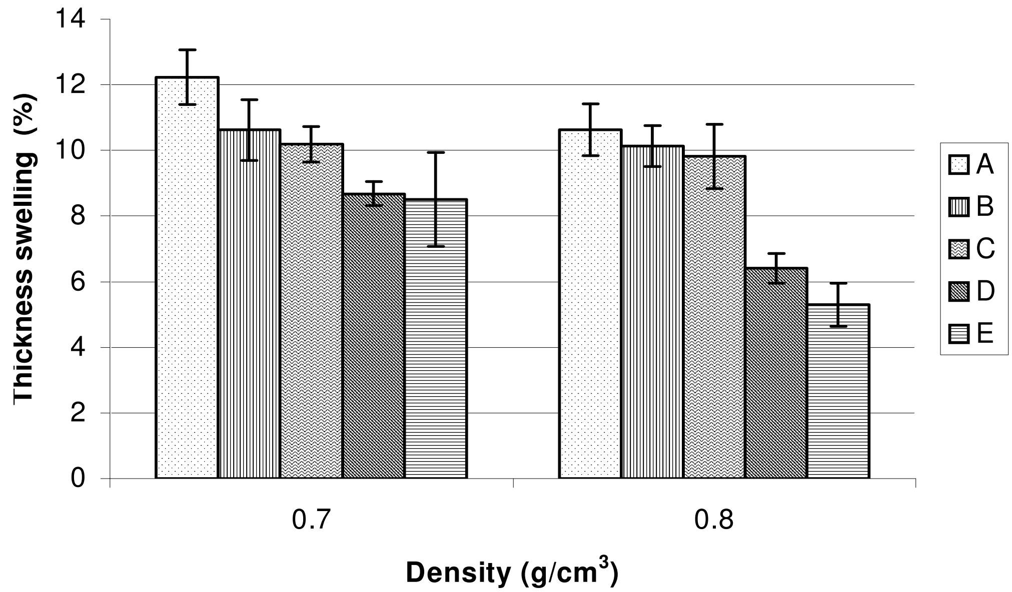

Figure 1. The 2 h thickness swelling of the panels.

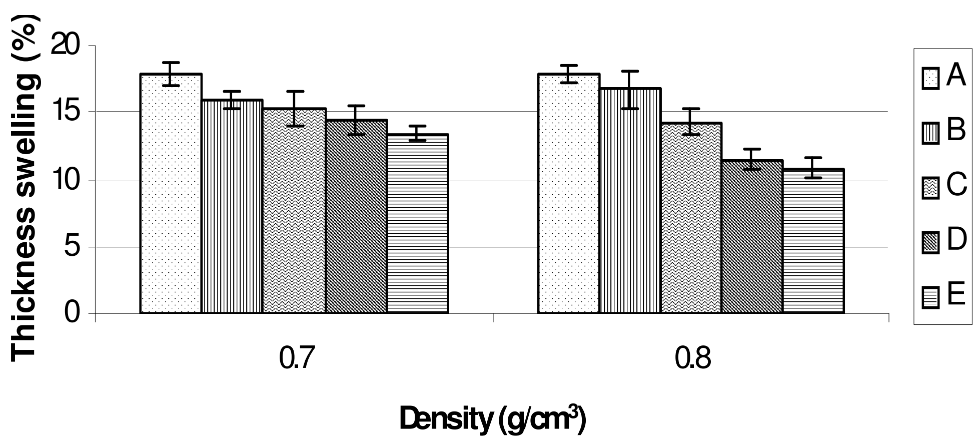

Figure 2. The 24 h thickness swelling of the panels.

stalk fiber. These three panels contained higher amount of corn stalks which have higher fiber aspect ratio. Its core panels contained soft parenchyma cells and they attract more water due to attractive OH groups. On the other hand, the lowest mean thickness swelling with more wood content (C, D and E for 2 and 24 h) could be explained by the compatibility of the furnishing, adhesive and fiber properties. The observed results indicated that the dimensional stability of the panels do not only depend on a specific factor, but could be altered by several factors mentioned above. In general, it seems that the dimensional stability of the panels get poorer as they include higher amount of corn stalks for both 2 and 24 h tests (Figures 1 and 2). This result was expected due to the chemical composition of the oak wood and corn stalks fibers. Corn stalks, including low amount of water resistant lignin and high amount of water attractive carbohydrates, resulted in higher amount of available OH groups for water.

The thickness swelling for 24 h was closer to the TS-EN 312 requirement (14%) for all boards produced in this study. This could be due to the usage of water repellent chemicals in board production. Normally, in similar studies with crop panels, higher thickness swelling values were observed as: 20, 22, 24, 25, 25, 26 and 27% for flax (Kozlowski and Piotrowski 1987), tobacco straw (Kalaycıoğlu, 1992), cotton stalks (Güler and Özen, 2004), hemp (Kozlowski and Piotrowski 1987), sunflower stalks (Bektas et al., 2005), cotton carpel (Alma et al., 2005) and tea plant waste (Kalaycıoğlu, 1992), respectively.

The water absorption values of fiberboards produced using corn stalks are significantly different depending on

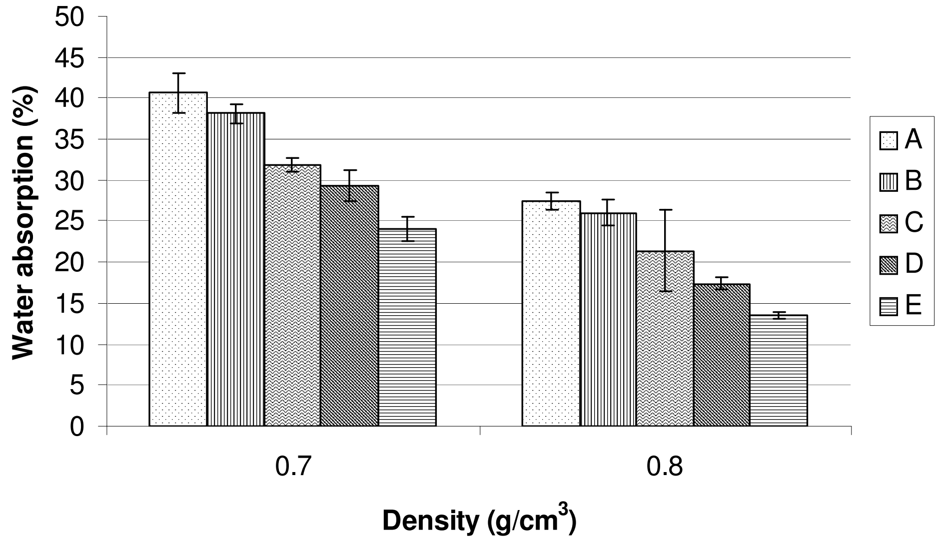

Figure 3. The 2 h water absorption of the panels.

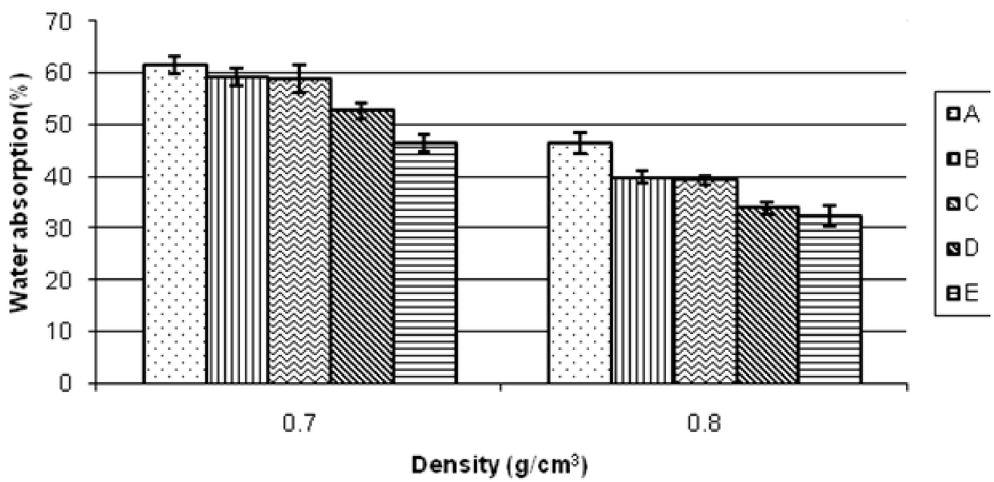

Figure 4. The 24 h water absorption of the panels.

the density ($p < 0.001$) and water immersion time ($p < 0.001$). Increase in soaking time, from 2 to 24 h as expected, results in higher water absorption values for the fiberboard (Figures 3 and 4). A significantly low amount of water was held by the panels as the panel density was increased from 0.7 to 0.8 g cm^{-3}. Denser fiberboards, having lower void spaces in the structure, were expected to absorb less water. This result is parallel to earlier finding in literature (Güler and Özen, 2004).

The results of ANOVA and Duncan mean separation tests for the bending strength (MOR), modulus of elasticity (MOE), internal bonding strength (IB) and surface hardness test results of the produced fiberboard are given in Table 5. The mean MOR and MOE for the fiberboard varied from 18.7 to 47.3N mm^{-2} and 3890 to 5078.1 N mm^{-2}, respectively (Figures 5 and 6). The boards produced met the minimum MOR (20 N mm^{-2}) required in TS-EN-310 (1999) standard for general pur-pose board (11). The minimum MOE indicated by the standard (1800 N mm^{-2}) for general purpose fiberboard was met by all panels. Results indicated that increasing board density had a positive effect on the MOR and MOE of the fiberboard ($p < 0.001$) and the highest MOR and MOE were observed with a panel of 0.8 g cm^{-3} density. Higher amount of corn stalks in the mixture resulted in an inferior effect on MOR. The best MOR and MOE were observed for panels that consisted of solely oak fibers. Similar results were also reported by other researchers for cotton carpel, hazelnut husk and kiwi prunings (Alma et al., 2005; Copur et al., 2007; Nemli et al., 2003).

The IB of the produced fiberboards varied from 0.22 to 0.72 N mm^{-2} (Figure 7). The minimum requirements in the

Table 5. Mechanical properties of MDF.

Mechanical property	Board type	Density	Mean [a]	Std. deviation	Std. error	X_{Min} [b]	X_{Max} [c]	p [d]
MOR (N mm^{-2})	A	0. 7	19. 9^{x}	4. 071	1. 820	16. 2	26. 4	**
		0. 8	30. 1^{y}	0. 987	0. 441	28. 4	30. 9	**
	B	0. 7	18. 7^{x}	1. 319	0. 590	17. 2	20. 5	*
		0. 8	33. 1^{y}	4. 327	1. 935	28. 1	38. 3	*
	C	0. 7	24. 4^{x}	1. 723	0. 770	22. 4	26. 7	**
		0. 8	35. 5^{y}	4. 364	1. 952	31. 4	42. 8	**
	D	0. 7	27. 1^{x}	1. 951	0. 873	23. 7	28. 4	*
		0. 8	37. 5^{y}	1. 761	0. 787	34. 9	39. 8	*
	E	0. 7	29. 9^{x}	2. 581	1. 154	27. 5	33. 3	**
		0. 8	47. 3^{y}	3. 078	1. 377	43. 8	51. 2	**
MOE (N mm^{-2})	A	0. 7	3792. 6^{x}	283. 30	126. 70	3499. 9	4238. 2	**
		0. 8	4278. 1^{y}	125. 95	56. 33	4125. 4	4451. 2	**
	B	0. 7	3890. 0^{x}	305. 08	136. 44	3621. 3	4291. 7	**
		0. 8	4573. 1^{y}	198. 98	88. 99	4332. 8	4826. 9	**
	C	0. 7	4048. 2^{x}	228. 65	102. 25	3761. 6	4390. 7	**
		0. 8	5021. 3^{y}	518. 95	232. 08	4568. 3	5598. 8	**
	D	0. 7	4035. 2^{x}	208. 99	93. 46	3763. 1	4290. 4	*
		0. 8	5017. 3^{y}	308. 16	137. 82	4550. 9	5409. 2	*
	E	0. 7	4095. 7^{x}	260. 86	116. 66	3686. 5	4393. 8	*
		0. 8	5078. 1^{y}	223. 16	99. 80	4838. 5	5444. 6	*
IB (N mm^{-2})	A	0. 7	0.22^{x}	0.064	0.029	0.13	0.28	**
		0. 8	0.41^{y}	0.083	0.037	0.33	0.54	**
	B	0. 7	0.52^{x}	0.074	0.033	0.43	0.60	NS
		0. 8	0.52^{x}	0.042	0.019	0.45	0.55	NS
	C	0. 7	0.45^{x}	0.109	0.049	0.37	0.63	NS
		0. 8	0.59^{x}	0.084	0.038	0.51	0.73	NS
	D	0. 7	0.70^{x}	0.105	0.047	0.54	0.82	NS
		0. 8	0.70^{x}	0.055	0.025	0.62	0.76	NS
	E	0. 7	0.70^{x}	0.064	0.028	0.63	0.77	NS
		0. 8	0.72^{x}	0.061	0.028	0.62	0.78	NS
Hardness (Nmm^{-2})	A	0. 7	62. 4^{x}	8. 566	2. 709	55	81	*
		0. 8	76. 9^{y}	8. 333	2. 635	64	85	*
	B	0. 7	65. 3^{x}	6. 430	2. 033	57	76	**
		0. 8	74. 8^{y}	4. 940	1. 562	65	81	**
	C	0. 7	67^{x}	4. 055	1. 282	62	74	*
		0. 8	76. 2^{y}	3. 824	1. 209	71	83	*
	D	0. 7	66. 6^{x}	3. 239	1. 024	62	71	*
		0. 8	75^{y}	3. 367	1. 065	68	79	*
	E	0. 7	67. 6^{x}	4. 169	1. 318	62	74	*
		0. 8	77. 5^{y}	4. 249	1. 344	71	86	*

[a]Mean values are the average of 10 specimens. [b]minimum value; [c]maximum value; [d]significance level; [*]significant at 0.001, [**]significant at 0.01, NS; non significant for ANOVA; [x,y]values having the same letter are not significantly different (Duncan test).

standards are 0.24 N mm^{-2} for general purpose (EN 312-2, 1996), 0.35 N mm^{-2} for interior fitments (EN 312-3, 1996) and load-bearing boards (EN 312-4, 1996) and 0.50 N mm^{-2} for heavy duty load bearing boards (EN 312-6, 1996). Results indicated that all produced fiberboard regardless of the panels' density met the minimum requirement for all purposes. Increase in board density led to an increase in IB properties ($p < 0.001$). Increasing

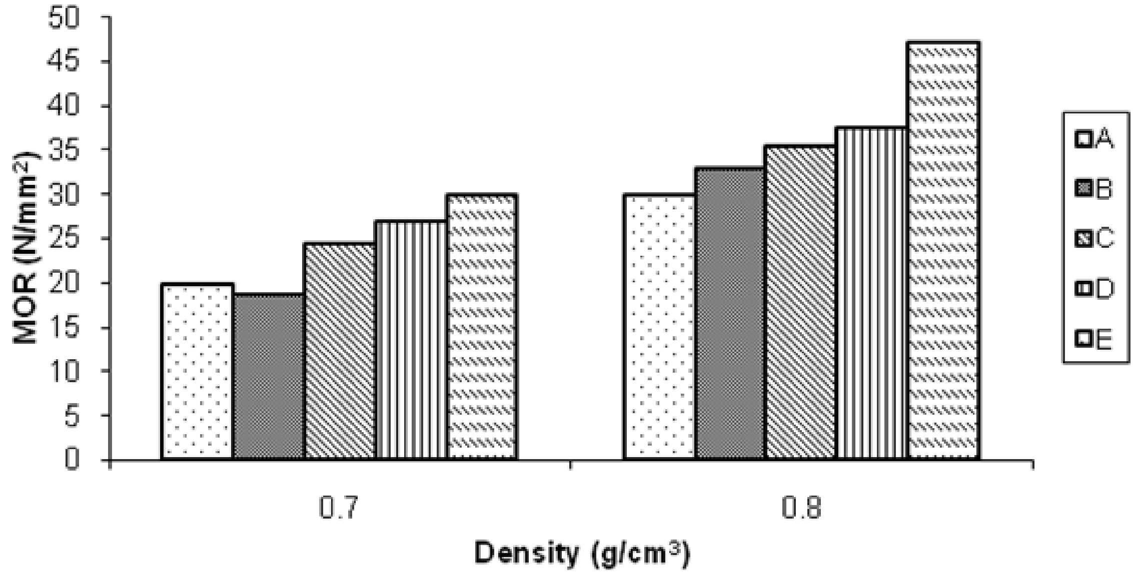

Figure 5. Bending strength of panels.

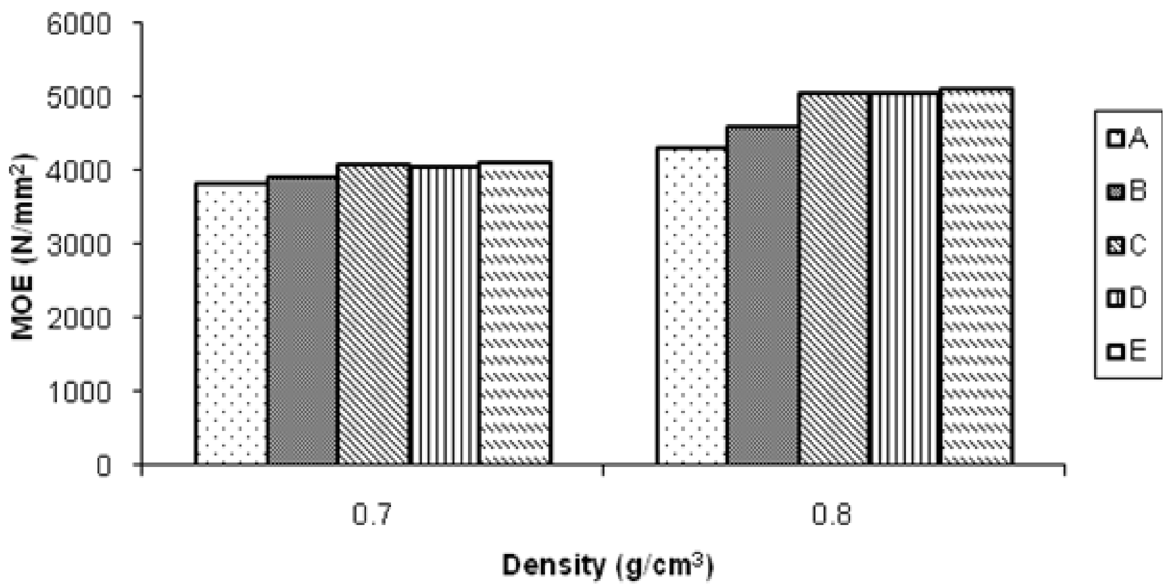

Figure 6. Modulus of elasticity of panels.

the amount of corn stalks in the mixture decreased the IB of the produced boards. Similar results have also been observed for other crop boards such as hazelnut husk (Copur et al., 2007).

The surface hardness of the produced boards showed that density of the boards affected the hardness of the boards. As a result, denser boards resulted in harder surfaces (Figure 8). The hardest panel surface was obtained with panels consisting of oak fibers. However, the differrence between MDF made from oak wood fiber and MDF made from corn stalk fiber is not significant.

Conclusion

Turkish economy relies mostly on agriculture sector. Turkey is known as the seventh country in the world in terms of farm output and it generates almost 54.5 million m^3 agricultural residues. Among these productions, a remarkable amount (4.2 million m^3) is corn stalks. Substitution of wooden material with corn stalks fiber could be used in MDF production. However, the addition of corn stalks fiber significantly decreases the hygroscopic and mechanical properties. Although, physical and mechanical properties

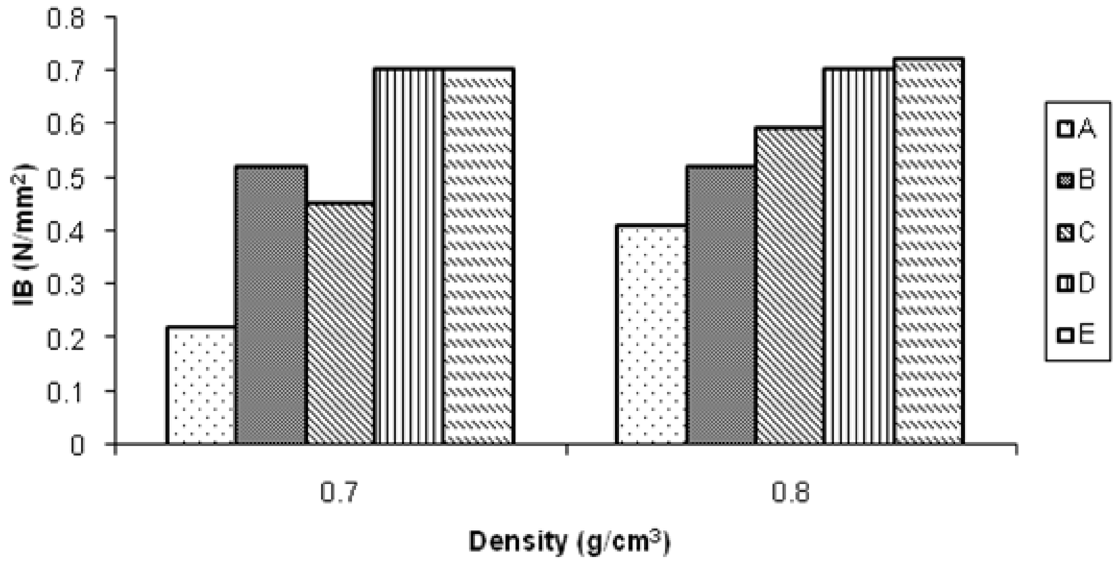

Figure 7. Internal bond strength of panels.

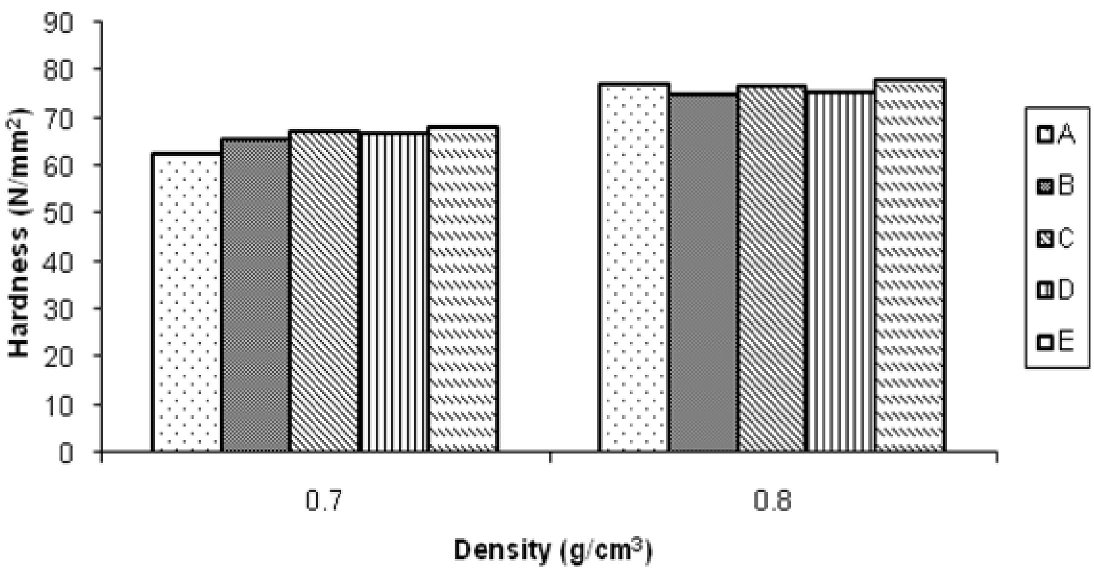

Figure 8. Janka hardness of panels.

are reduced with the addition of corn stalks fiber, board mechanical properties fulfill the requirements of European standards. In general, it is possible to produce fiberboards without falling below the properties required in the standards.

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