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Biochemical and textural changes in trifoliate yam *Dioscorea dumetorum* tubers after harvest

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Abstract

Biochemical and textural changes were investigated in trifoliate yam *Dioscorea dumetorum* tubers, after harvest, in an attempt to study the chemical and physical changes associated with the raw and cooked tubers and how these relate to the hardening phenomenon of the tubers after harvest. A 2×2×3×4 factorial experiment, with cultivar, storage condition, treatment and storage time as their respective variables, was done. Samples were analysed for moisture, starch, reducing sugars, alcohol-soluble sugars, acid and neutral detergent fibre, cellulose, hemicellulose and lignin. The Warner–Bratzler test cell was used in a TA.XT2 Texture Analyser to measure the hardness of cooked tubers. The moisture and starch contents of the tubers decreased from 77.8 to 70.4% and 70.5 to 66.5 g/100g, respectively in a period of 72 h of storage, suggesting rapid dehydration after harvest and breakdown of starch. All the other chemical indices increased with storage time. These changes were influenced by the storage temperature and the treatment given to the tubers prior to storage. In general, samples stored at 4 °C showed smaller changes in the chemical indices than those at 28 °C, suggesting a temperature-dependence of the changes. Both cultivars of yam showed increase in hardness with storage time. A high correlation ($r = 0.9503$–0.9913) was noted between the texture and the chemical indices of the white cultivars. Storage of the trifoliate yam, *Dioscorea dumetorum,* immediately after harvest, leads to reduction in moisture and starch contents and increase in sugars and structural polysaccharides. Low temperature storage may reduce the hardening phenomenon. A mechanism for the hardening phenomenon has been proposed.

Keywords: *Dioscorea dumetorum*; Raw; Cooked; Physical changes; Chemical changes; Biochemical changes; Textural changes; Post-harvest storage

1. Introduction

Yams belong to the *Dioscorea* genus and are staple foods of cultural, economic and nutritional importance in the tropics, which produce edible starchy storage tubers (Coursey, 1967). *Dioscorea dumetorum* is an important food security crop and, of the six yam species mostly consumed in west Africa, *D. dumetorum* is the most nutritious. *Dioscorea dumetorum* originated in tropical Africa and occurs in both wild and cultivated forms but its cultivation is still restricted in west and central Africa (Degras, 1993; King & Hackett, 1983).

It has a fairly high protein content of 9.43–10.3% (dry weight basis; Afoakwa & Sefa-Dedeh, 2001) as compared to the protein contents of 8.2 and 7.6% (dry weight basis) reported for water yam *(D. alata)* and white yam *(D. rotundata),* respectively (Agbor-Egbe & Treche, 1995). It has also been reported that *D. dumetorum* protein is well balanced in the amino acids (with a slight deficiency of lysine) and has an average chemical score of 93 (against 86 for *D. rotundata),* when compared to the FAO/WHO (1973) reference protein.

Agronomically, *D. dumetorum* is high-yielding, with yields of 10 and 40 tonnes/hectare recorded under traditional farming conditions and in agricultural stations, respectively (Lyonga & Ayuk-Takem, 1979; Ngong-Nasah, Lyonga, & Ayuk-Takem, 1980). Unlike the other yams, staking is not necessary to maintain yield (Lyonga & Ambe, 1985) and the tubers grow near the surface of the soil. This saves labour and allows for mechanization of harvest. Whereas all other yam species have a long shelf-life, which does not affect their cooking and organoleptic qualities and can be available all year round, *D. dumetorum* is consumed exclusively during its limited harvest period because of a post-

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harvest hardening phenomenon which reduces its storage durability.

The hardening of *D. dumetorum* tubers is a serious handicap and begins a few hours after harvest. The tubers become hardened and resistant to chewing and cooking, even after long hours of cooking (Treche & Delpeuch, 1982), thus making their consumption impossible. The high perishability of *Dioscorea dumetorum* tubers is manifested in a loss of quality, which is suspected to be brought about by the endogenous biochemical reactions of the tuber, leading to unacceptable textural characteristics. This calls for an in-depth investigation to elucidate the basis of the adverse effect and suggest suitable control measures for storage.

The purpose of this study was to investigate the chemical and physical changes associated with the raw and cooked *D. dumetorum* tubers and to determine how they relate to the hardening phenomenon.

2. Materials and methods

2.1. Materials

Two cultivars (white and yellow) of trifoliate yam tubers were harvested (matured) from a farm at Obomeng in the eastern Region of Ghana and divided into three main groups. One group of tubers was heat-treated by boiling in water for one hour and allowed to cool. The second sample was cut into pieces 5 cm thick and 5 cm diameter, whilst the third group was left as whole tubers. Each of these three groups was further sub-divided into two, one group being kept in an ice-chest container packed with ice cubes to keep the tubers in low temperature conditions (28 °C). The other group was packaged in box containers and then transported to the laboratory (within 3 h of harvest) for subsequent analysis.

At the laboratory, the samples kept in the ice-chest containers were stored under cold room temperature conditions (4 °C), whilst the others were stored under tropical ambient temperature conditions (28 °C) for a period of 0, 24, 36 or 72 h.

2.2. Experimental design

A 2×2×3×4 factorial experimental design was used and the principal factors were:

1. Types of cultivar: White and yellow
2. Storage conditions: Tropical ambient (28 °C) and Cold Room (4 °C) temperatures.
3. Sample treatments: Heat treatment (Cooked), untreated whole tubers (Whole) and untreated chopped tubers (Chopped).
4. Storage periods: 0, 24, 48 and 72 h

2.2.1. Sample preparation for biochemical analyses

The samples were peeled, washed and cut into slices of 0.5 cm thickness and 5.0 cm diameter using a Hobart cutter. The slices were then freeze-dried using an Edwards bench freeze-drier (Edwards Instruments Ltd., Homchurch, Essex). Prior to biochemical analyses, the freeze-dried samples were ground in a Hammer mill (Christy and Norris Ltd, England) into flour to pass through a 250-μm sieve. The flour samples obtained were packaged into polypropylene bags and kept under ambient temperature conditions (28 °C) for analyses.

Samples were analyzed for moisture, starch, total alcohol-soluble sugars, reducing sugars and sucrose contents. Plant cell wall polysaccharide constituents, comprising acid detergent fibre, neutral detergent fibre, lignin, cellulose and hemicellulose contents, were also determined. The data were subjected to analyses of variance.

2.3. Analytical methods

The samples were analysed in triplicate for moisture content using Association of Official Analytical Chemist Approved methods 925.10 AOAC (1990). Starch was determined using the ferricyanide (acid hydrolysis) method described by AOAC (1984), as modified by Bainbridge, Tomlins, Wellings, and Westby (1996). Total alcohol-soluble sugars and reducing sugars were determined by the spectrophotometric procedure described by Bainbridge et al. (1996). Lignin and acid detergent fibre contents were estimated using AOAC (1990) methods. Neutral detergent fibre levels were also determined gravimetrically by the procedure of Bainbridge et al. (1996). Cellulose and hemicellulose contents were determined by the procedures described by Van Soest and Wine (1967).

2.4. Texture analysis

The yams were cooked in boiling water (100 °C) for 1 h on a hot plate and made to cool completely at room temperature (28 °C). The cooked tubers were cut into slices of 1 cm thickness and 5 cm diameter, and evaluated using a Warner–Bratzler test cell in a TA.XT2 Texture Analyzer (Stable Micro Systems, Haslemere, Surrey, England). The cooked samples were analyzed for their textural properties using TA. XT2 Texture Analyzer. The TPA parameters were calculated using the computer software XT.RA Dimension V3.7L, which allows capturing, storage and analysis of the real-time data generated from the experimental runs with the TA.XT2. The following test parameters were used: pre-test speed: 10 mmls, test speed: 5.0 mm/s, post-test speed 10 mm/s, distance: 20 mm. The peak force required to cut completely through the slices as well as the area under the curve were recorded as the levels of

hardness and adhesiveness, respectively. Determinations were done in triplicate.

2.5. Statistical analyses

The data obtained from the biochemical and textural analyses were statistically analyzed using Statgraphics (Graphics Software System, STCC, Inc. USA). Comparisons between sample treatments and the indices were done using analysis of variance (ANOVA) and correlation analysis with a probability $P \leqslant 0.05$.

3. Results and discussion

3.1. Biochemical studies

The moisture content of the white and yellow cultivars of *D. dumetorum* tubers showed no major differences during the storage period. Moisture levels of the white cultivars kept at 28 °C decreased from 77.82–72.08% for the whole tubers during the 72 h of storage whilst the tubers chopped into pieces prior to storage decreased from 77.82 to 70.43%. The yellow cultivars showed similar decreasing trends for the whole tubers and tubers chopped before storage (Fig. 1). This means that, within 72 h of harvesting, there was about 8–12% moisture loss in the tubers investigated, which indicates general decreases in moisture content in both cultivars with storage time (Fig. 1). This suggests that the tubers undergo a process of rapid dehydration immediately after harvesting, leading to the hardening phenomenon. Treche and Agbor-Egbe (1996) reported moisture losses of 31% in *D. rotundata* and 35% in *D. dumetorum* tubers after 110 days in storage. The effect of this rapid water removal in the tubers might have brought the cell wall polysaccharides closer together, permitting greater interaction by means of hydrogen bonding and van der Waals forces, resulting in increased cell rigidity during storage of the tubers.

The sample treatment by which the tubers were chopped into pieces before storage was observed to facilitate the rate of moisture loss as compared to the whole tubers during storage and no significant variations in moisture content were observed for the cooked samples with storage time. Low temperature storage of tubers, however, reduced the rate of moisture loss considerably as compared to the rates observed for the tubers stored under tropical ambient conditions. This observation suggests that storage of the tubers at 4 °C retards the rate of dehydration in the tubers. Statistical analysis of the data showed that cultivar, sample

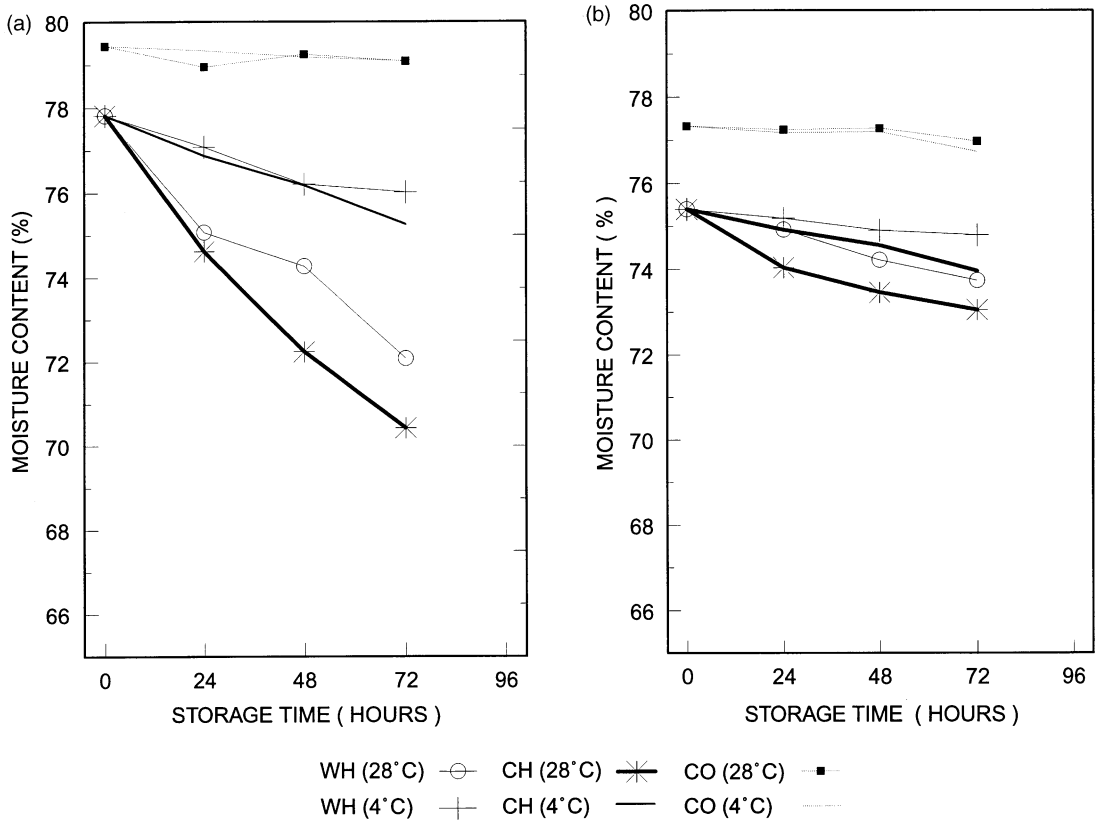

Fig. 1. Changes in moisture content of white (a) and yellow (b) cultivars of trifoliate yam tubers during storage.

Table 1
F-values of process variables for moisture and carbohydrate contents of *Dioscorea dumetorum* tubers

Process variables	Moisture	Starch	Total alcohol-soluble sugars	Reducing sugars
Cultivar	226.460	94.284	523.885	83.250
Sample treatment	169.904	3.346	32.586	12.595
Storage condition	12.232	3.531	8.226	11.760
Storagetime	18.700	5.113	6.892	5.825

*Significant at $P \leqslant 0.05$.

treatment, storage condition and storage time all significantly affected ($P \leqslant 0.05$) the moisture contents of the tubers (Table 1).

Starch breakdown has been widely reported as the major factor causing decrease in weight of the yam tuber and its rate of degradation determines the half-life of the tuber (Moore, 1984; Oti, 1981; Treche, 1984). The starch storage system showed an interesting trend with slight fluctuations during the storage of the white and yellow cultivars for up to 72 h. Starch levels of the white tubers generally decreased with storage time (Fig. 2a) with no noticeable change in the yellow tubers with all the treatments (Fig. 2b). The decreasing trend in the white cultivars was more pronounced in the tubers stored at 28 °C than in those stored at 4 °C, and to a greater extent with the samples chopped into pieces before storage. This indicates that low temperature storage of the tubers retards the rate of decrease in starch content during storage. The decrease in starch after harvest also appears to be retarded by cooking (Fig. 2). This, however, suggests that there is a rapid degradation of starch in the white tubers after harvest and it is believed that the reactions involved in their metabolism play important roles in the post-harvest changes of the tuber. Analysis of variance on the data showed that the cultivar, sample treatment, storage condition and storage time all had a significant effect ($P \leqslant 0.05$) on the starch content of the tubers during storage (Table 1). These changes are therefore largely dependent on conditions of storage such as temperature and time.

The total alcohol-soluble sugars were observed to increase significantly with storage time (Fig. 3). This trend was similar in the two cultivars studied, even though the rate of increase was relatively low in the

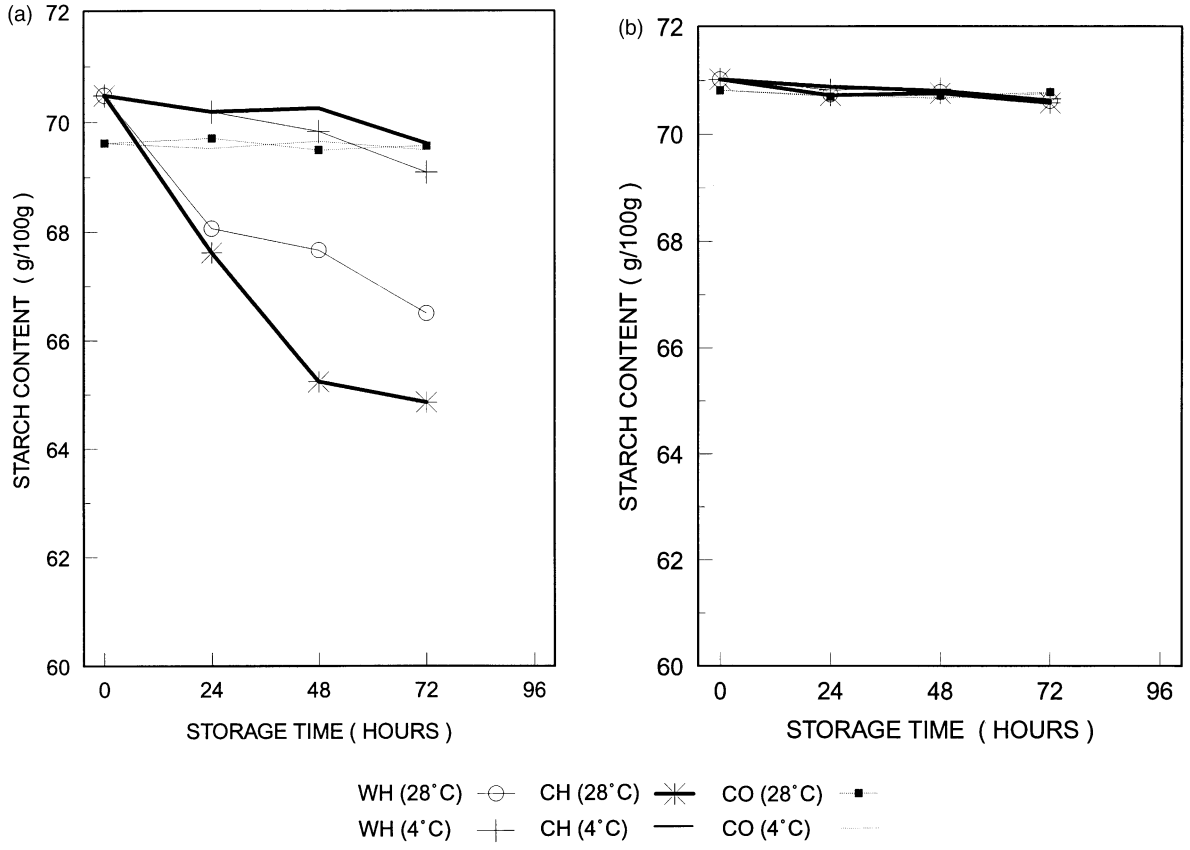

Fig. 2. Changes in starch content of white (a) and yellow (b) cultivars of trifoliate yam tubers during storage.

yellow cultivars. The tubers chopped into pieces before storage showed a comparatively rapid rate of increase in the total alcohol-soluble sugar levels in the tubers as compared to the whole tubers, and no significant variations were observed for the cooked samples with storage time (Fig. 3). These increases, observed during storage of the tubers, might be the result of hydrolysis of starch into sugars after harvesting which has been reported (Treche & Agbor-Egbe, 1996) to be the most predominant change occurring in the tubers after harvest. Low temperature storage of the tubers, however, minimized the rate of increase in the total alcohol-soluble sugars levels during storage. Statistical analysis indicated that the cultivar, sample treatment, storage condition and storage time all significantly affected ($P \leqslant 0.05$) the total alcohol-soluble sugar levels in the tubers during storage (Table 1).

The results indicate that the reducing sugar levels were generally affected by storage time. Storage caused a rapid increase in reducing sugar levels of the white cultivars, while only slight increases were observed in the yellow cultivars (Fig. 4). Earlier studies reported very high increases in reducing sugar levels during storage of *D. dumetorum* tubers (Treche & Agbor-Egbe, 1996). The different treatments given to the tubers prior to storage, such as cooking and chopping into pieces, however showed varied changes in reducing sugar levels with storage time and temperature. Marked increases in reducing sugars were noted in the tubers chopped into pieces before storage than in the whole tubers during the storage period at 28 °C. However, only slight increases in reducing sugars were observed in the tubers stored kept at 4 °C and no significant variations in reducing sugar levels were noted in the cooked samples during storage. These rapid increases in reducing sugar levels of the tubers during storage might have occurred as a result of the breakdown of starch molecules into sugars after harvest, causing the amount of reducing sugars to increase. Analysis of variance showed that the sample treatment, cultivar, storage condition and storage time all had significant effects ($P \leqslant 0.05$) on the reducing sugar levels of the tubers during storage (Table 1).

It was found that the freshly harvested *D. dumetorum* tubers had very high levels of acid and neutral detergent fibres. In both cultivars studied, rapid increases in acid and neutral detergent fibre contents were found with values, respectively, from 6.242–7.022% and 6.876–7.486% for the white cultivars and 6.561–6.928 and 6.925–7.282 during the storage period (Figs. 5 and 6). Earlier studies reported very high increases in acid and neutral detergent fibre content, during storage of *D. rotundata* and *D. dumetorum* tubers (Brillouet, Treche, & Sealy, 1981; Treche & Delpeuch, 1982; Treche & Agbor-Egbe, 1996). The acid and neutral detergent fibre contents of the tubers increased with storage time

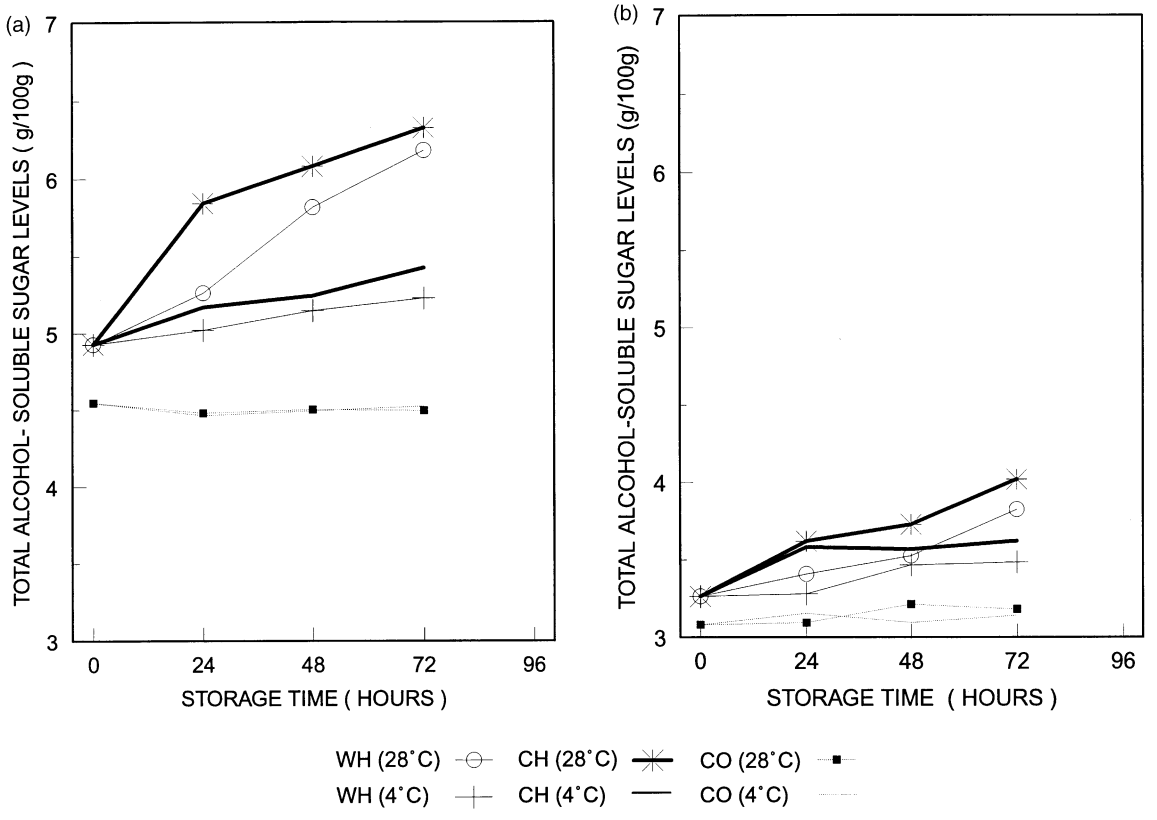

Fig. 3. Changes in reducing sugar levels of white (a) and yellow (b) cultivars of trifoliate yam tubers during storage.

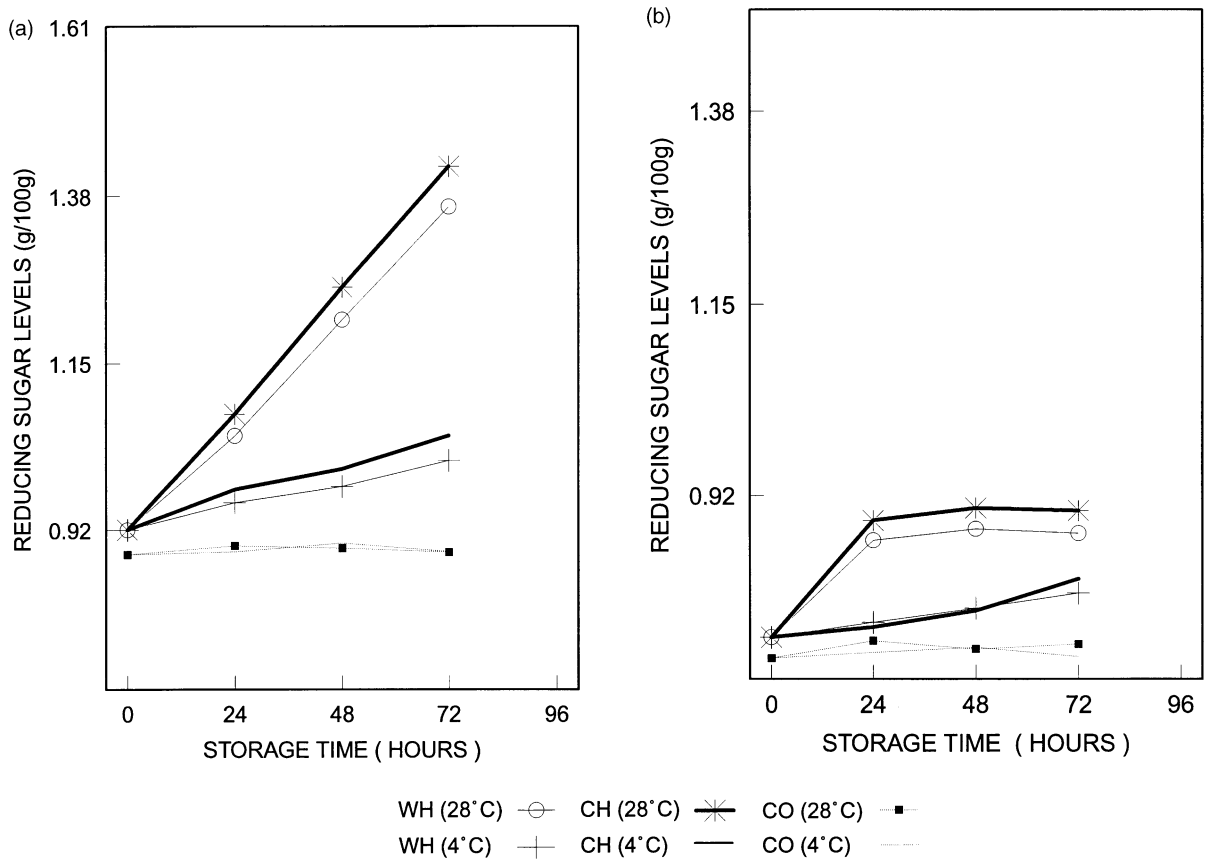

Fig. 4. Changes in total alcohol-soluble sugar levels of white (a) and yellow (b) cultivars of trifoliate yam tubers during storage.

(Figs. 5 and 6). The tubers chopped into pieces prior to storage showed more rapid increases in both acid and neutral detergent fibre contents during the storage period than the whole tubers, but no observable change was noted for the cooked tubers. Furthermore, low temperature storage of the tubers influenced the data by slowing down the rate of increase in the fibre levels in both cultivars during storage. These increases observed in the acid and neutral detergent fibre contents of the tubers during storage may be attributed to the hardening phenomenon which occurs in the tubers a few hours after harvest. This observation is suspected to be one of the determining factors leading to the hardening of the tubers after harvest. Statistical analysis showed that the sample treatment, cultivar, storage condition and storage time all had significant effects ($P \leqslant 0.05$) on the acid and neutral detergent fibre contents during storage of *D. dumetorum* tubers (Table 2).

A proper knowledge and understanding of the changes associated with lignin contents of yam tubers is necessary because of the role that lignin plays in conferring rigidity and toughness to plant cell walls. Generally, the lignin contents of both cultivars studied were observed to increase with storage time (Fig. 7). The mean values of the freshly harvested white cultivars were found to increase from 0.142 to 0.427 g/100 g during the 72-h storage period. The tubers chopped into pieces prior to storage, however, increased from 0.142 to 0.488 g/100 g when stored at 28 °C. This means that the treatment given to the tubers before storage influences their rate of lignification during storage. However,

Table 2
F-values of process variables for the plant cell wall carbohydrate contents of *Dioscorea dumetorum* tubers

Process variables	Acid detergent fibre	Neutral detergent fibre	Lignin	Cellulose	Hemicellulose
Cultivar	71.165	8.007	–	8.606	45.189
Sample treatment	69.667	151.832	8.080	28.098	96.810
Storage condition	13.750	7.033	5.893	17.102	21.694

*Significant at $P \leqslant 0.05$.

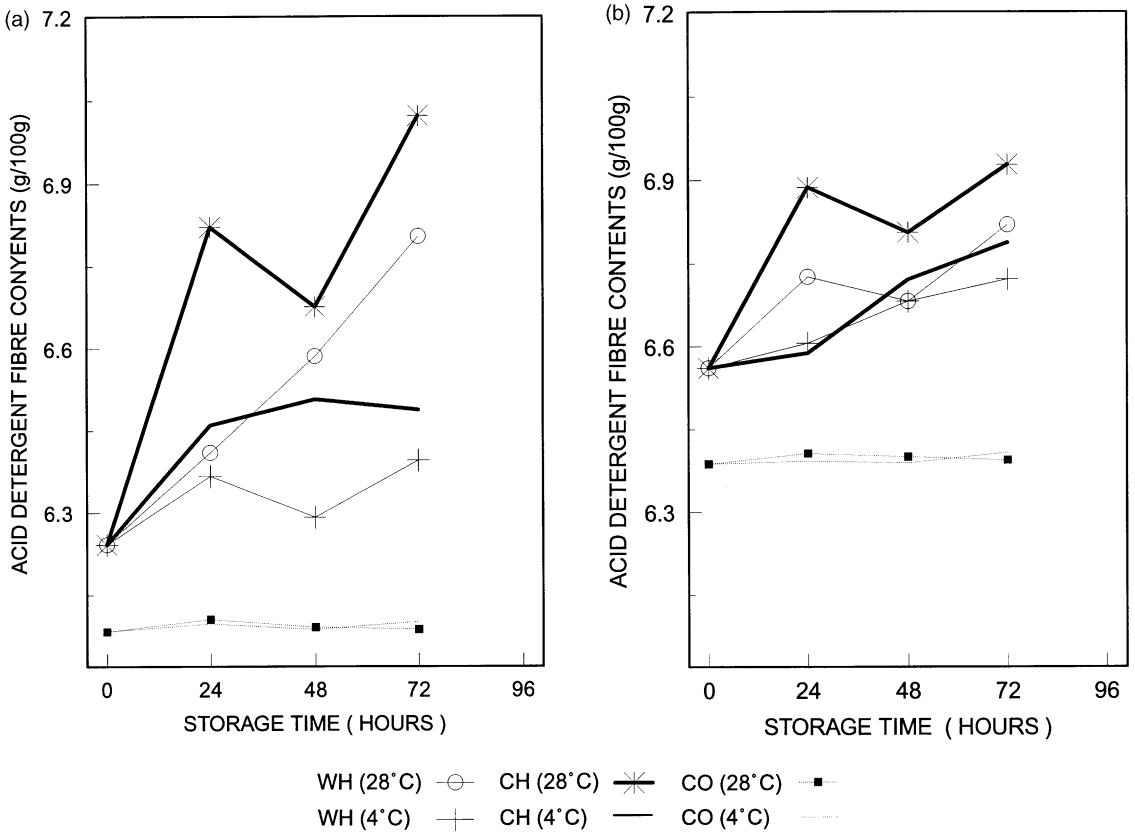

Fig. 5. Changes in acid detergent fibre content of white (a) and yellow (b cultivars of trifoliate yam tubers during storage.

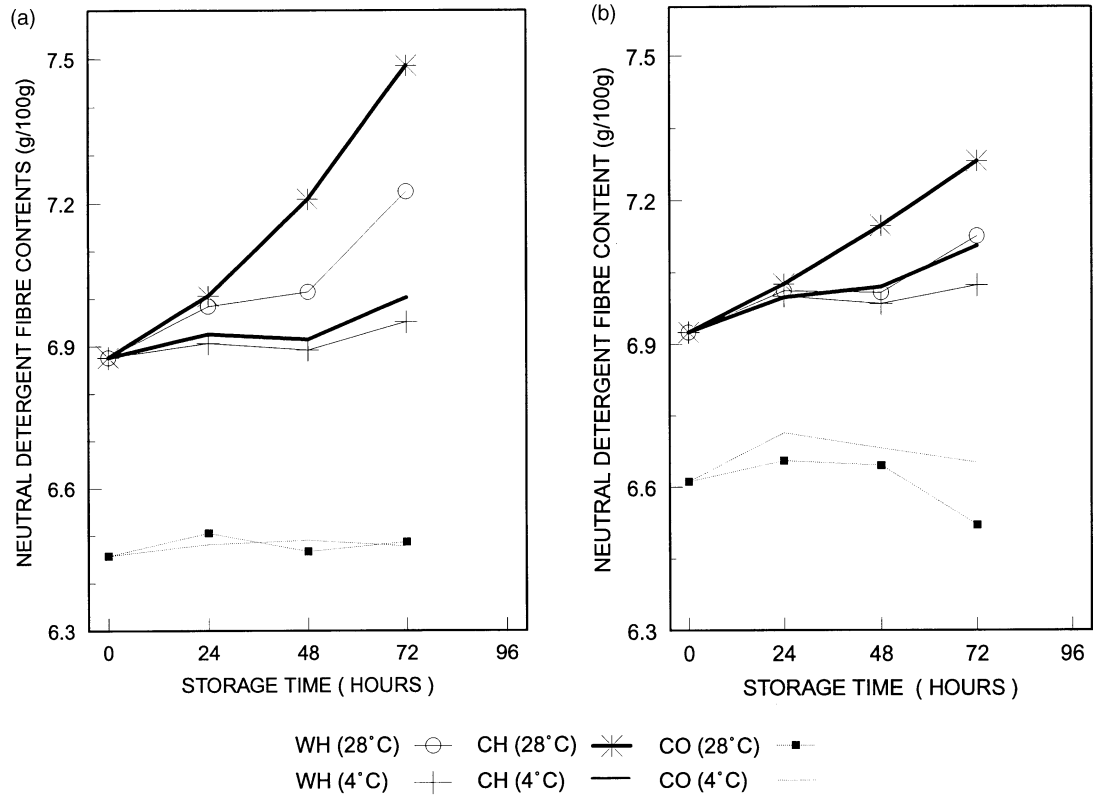

Fig. 6. Changes in neutral detergent fibre content of white (a) and yellow (b) cultivars of trifoliate yam tubers during storage.

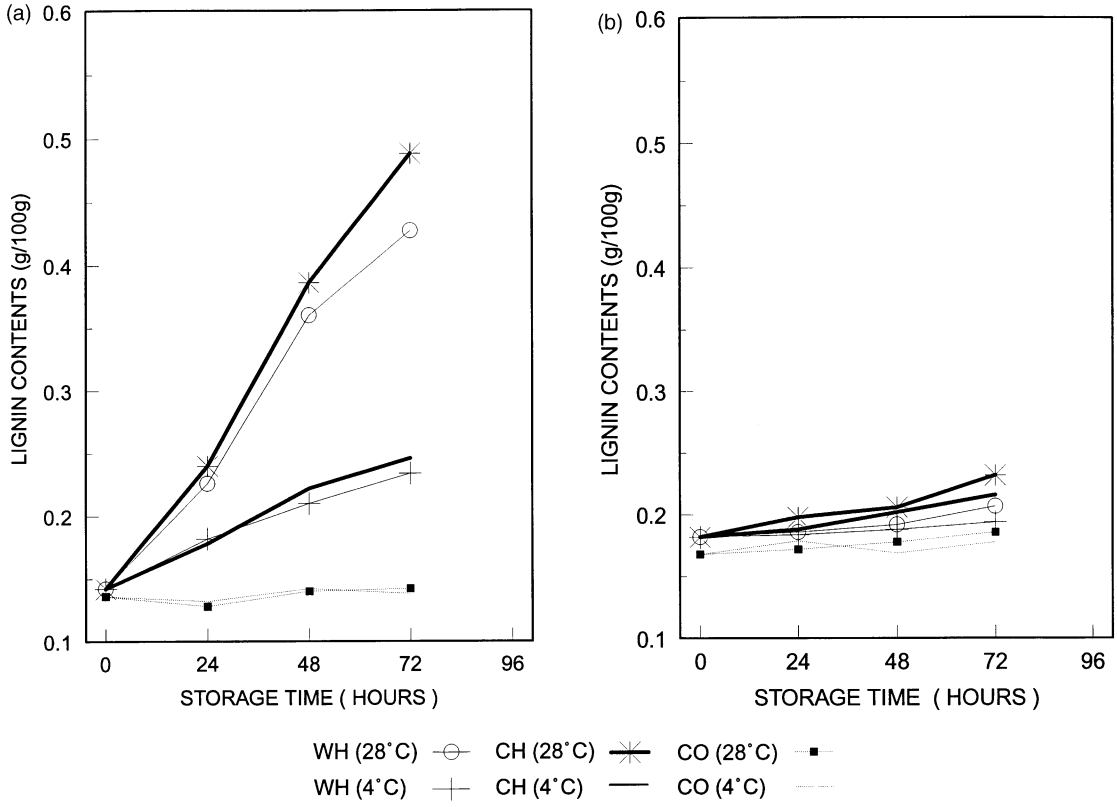

Fig. 7. Changes in lignin content of white (a) and yellow (b) cultivars of trifoliate yam tubers during storage.

comparatively lower trends were observed for the tubers stored at 4 °C. The increase in lignin contents of *D. dumetorum* tubers during storage is suggested to result from a rapid lignification process that occurs in the tubers after harvest. This process is believed to be brought about by the synthesis of polymers in the tubers which produces secondary thickening and acts as hydrophobic filler, forming condensed links with the constituents of the cell wall, thereby providing rigidity. Lignification of cell walls has been reported to confer rigidity and toughness to plant cell walls causing, textural changes (Goodwin & Mercer, 1992; Moore, Clark, Stern, & Vodopich, 1995). Analysis of variance showed that the sample treatment, storage condition and storage time all significantly affected ($P \leqslant 0.05$) the lignin contents of the tubers during storage (Table 2).

Cellulose is generally believed to play a very important role in the development of plant cell walls. Therefore, quantitative changes in the cellulose contents of yam tubers after harvest will presumably affect their textural properties. Storage was generally observed to increase the cellulose contents of *D. dumetorum* tubers (Fig. 8). The study revealed that the rate of increase in cellulose contents in the white cultivars were high with mean values ranging from 3.012 to 3.815 g/100 g for the whole tubers whilst the tubers chopped into pieces prior to storage increased from 3.012 to 4.016 g/100 g (Fig. 8). This means that the rate of increase in cellulose contents in the tubers, chopped into pieces prior to storage, was comparatively higher than those observed for the whole tubers during storage. However, relatively lower increases were found in the cultivars stored at 4 °C than in those stored at 28 °C. This indicates that the change in cellulose contents in the tubers is influenced by storage temperature and time. Increase in cellulose content of the tubers during storage is attributed to the hardening phenomenon that the tubers undergo after harvest. However, the additional cellulose is probably brought about by a rapid polymerization of pentose and xylose polymers in the tuber, resulting in the deposition of additional cellulose microfibrils, thereby causing textural changes in the tubers with time, since it has been reported (Moore et al., 1995) that the deposition of cellulose microfibrils originates in the polymerization of pentose and xylose polymers in plant tissues. Statistical analysis conducted indicated that the sample treatment, cultivar, storage condition and storage time all had significant effects ($P \leqslant 0.05$) on the cellulose contents of the tubers during storage (Table 2).

There was a general increase in hemicellulose contents of both cultivars during storage (Fig. 9). The white cultivars increased rapidly with mean values ranging from 4.282 to 4.927 g/100 g whilst the yellow cultivars increased from 4.564 to 4.788 g/100 g during the storage period. This explains that storage of the tubers at 28 °C showed comparatively higher rates of significant ($P \leqslant 0.05$)

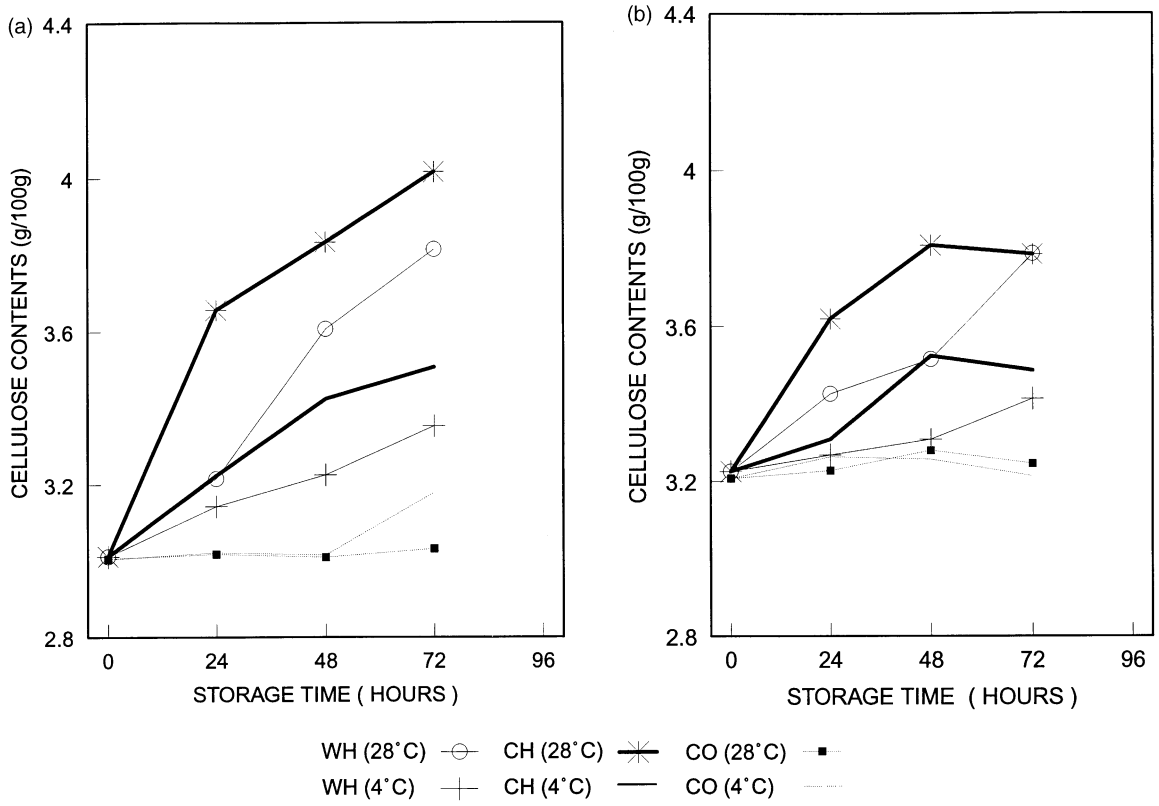

Fig 8. Changes in cellulose content of white (a) and yellow (b) cultivars of trifoliate yam tubers during storage.

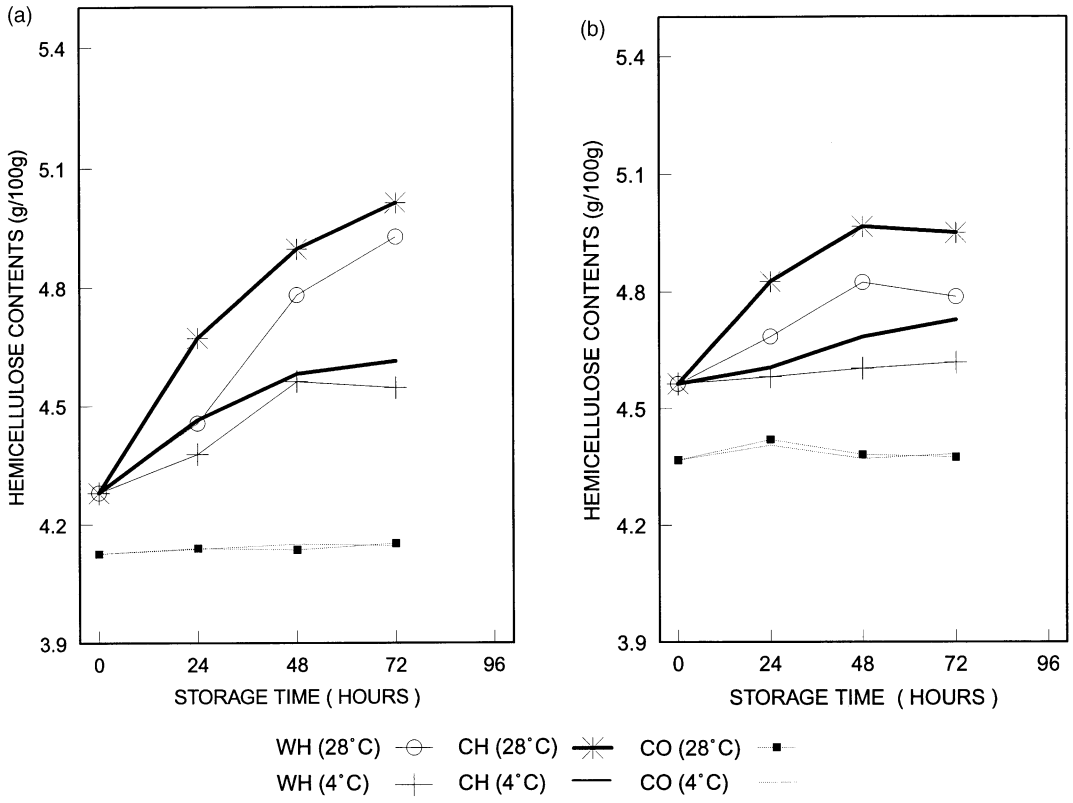

Fig. 9. Changes in hemicellulose content of white (a) and yellow (b) cultivars of trifoliate yam tubers during storage.

increase than those stored at 4 °C. Moreover, the tubers chopped into pieces prior to storage showed relatively higher rates of increase, ranging from 4.282 to 5.012 g/100 g during storage of the white cultivars as compared to 4.282–4.927 g/100 g (Fig. 9) for the whole tubers, but no significant variations were found in the cooked tubers during storage. Earlier studies (Treche & Delpeuch, 1979) found similar trends during prolonged storage studies of *D. rotundata* and *D. dumetorum* tubers. These increases in the hemicellulose contents of the tubers during storage might have resulted in the rapid hardening phenomenon of the tubers after harvesting. Moore et al. (1995) and Goodwin and Mercer (1992) reported that the deposition of the glucomannan and arabinoxylan matrix of hemicelluloses causes secondary thickening in plant cell walls. Hence, the observed increases in hemicellulose contents in the tubers during storage might have been brought about by the epimerization of sugar units within the tubers. This causes deposition of additional hemicellulosic matrix, thereby causing the cell wall to thicken during storage. Therefore, the increasing level of hemicelluloses during storage of *D. dumetorum* tubers is suspected to be one of the factors leading to the hardening phenomenon after harvest.

Statistical analysis indicated that the sample treatment, cultivar, storage condition and storage time all significantly affected ($P \leqslant 0.05$) the hemicellulose contents of the tuber during storage (Table 2).

3.2. Texture studies

The TA.XT2 Texture Analyzer was used for the measurement of the textural properties of the *D. dumetorum* tubers after harvesting. Measurements were made from the cooked samples of the freshly harvested tubers and after every 24 h in storage, for a period of 72 h to find the changes occurring in the textural properties of the tubers after harvesting. Peak forces of the curves, generated by the Texture Analyzer, were recorded as the hardness of the samples and the area under the curves was recorded as adhesiveness.

Hardness and curve area of the yam tubers, determined by the Warner–Bratzler blade, increased significantly during the storage period (Figs. 10 and 11). Apart from the stored cooked tubers, which did not show any variation in hardness and curve area, as compared to the freshly harvested tubers, the whole and chopped tubers increased consistently with storage time. However, the chopped tubers showed comparatively higher levels of hardness and curve area during the period of storage. These high levels of hardness and curve areas are probably due to the increase in surface area of the tubers, as exposed to the external environment, which might have facilitated biochemical reactions leading to the hardening phenomenon in the tuber after harvest.

Low temperature storage of the samples minimized the rate of hardening of the tubers during storage

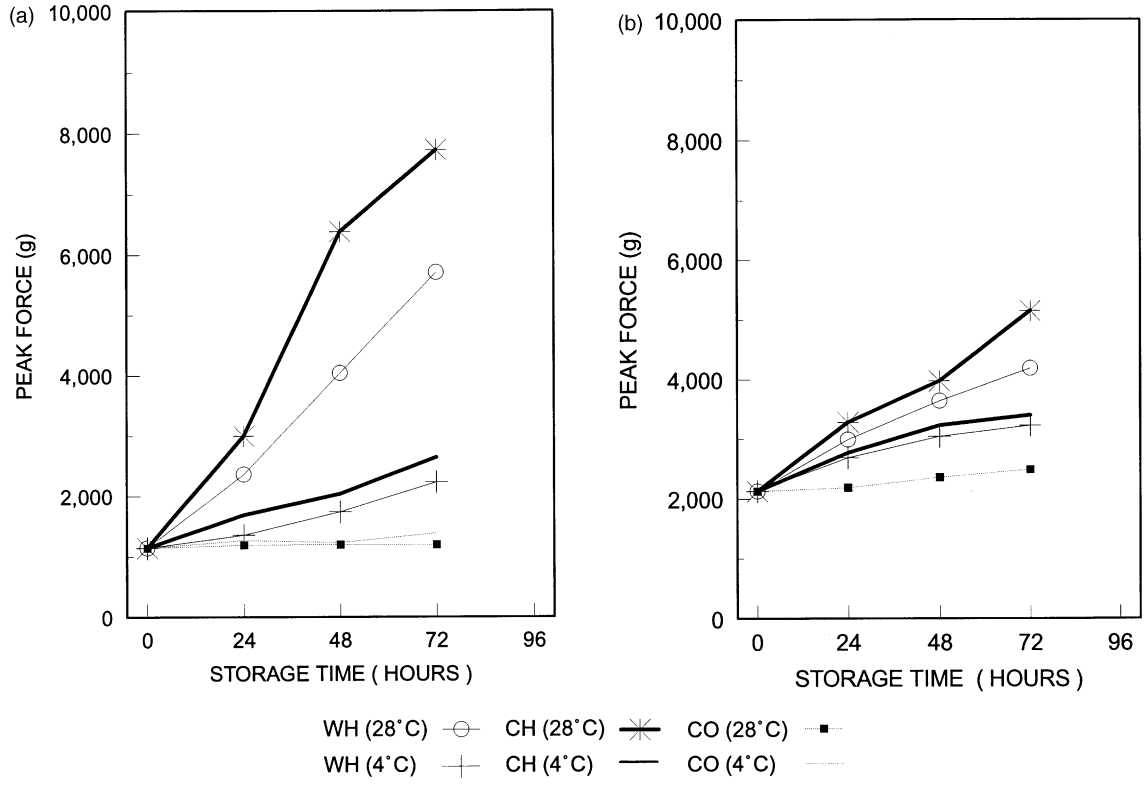

Fig. 10. Changes in peak force (hardness) of white (a) and yellow (b) cultivars of trifoliate yam tubers during storage.

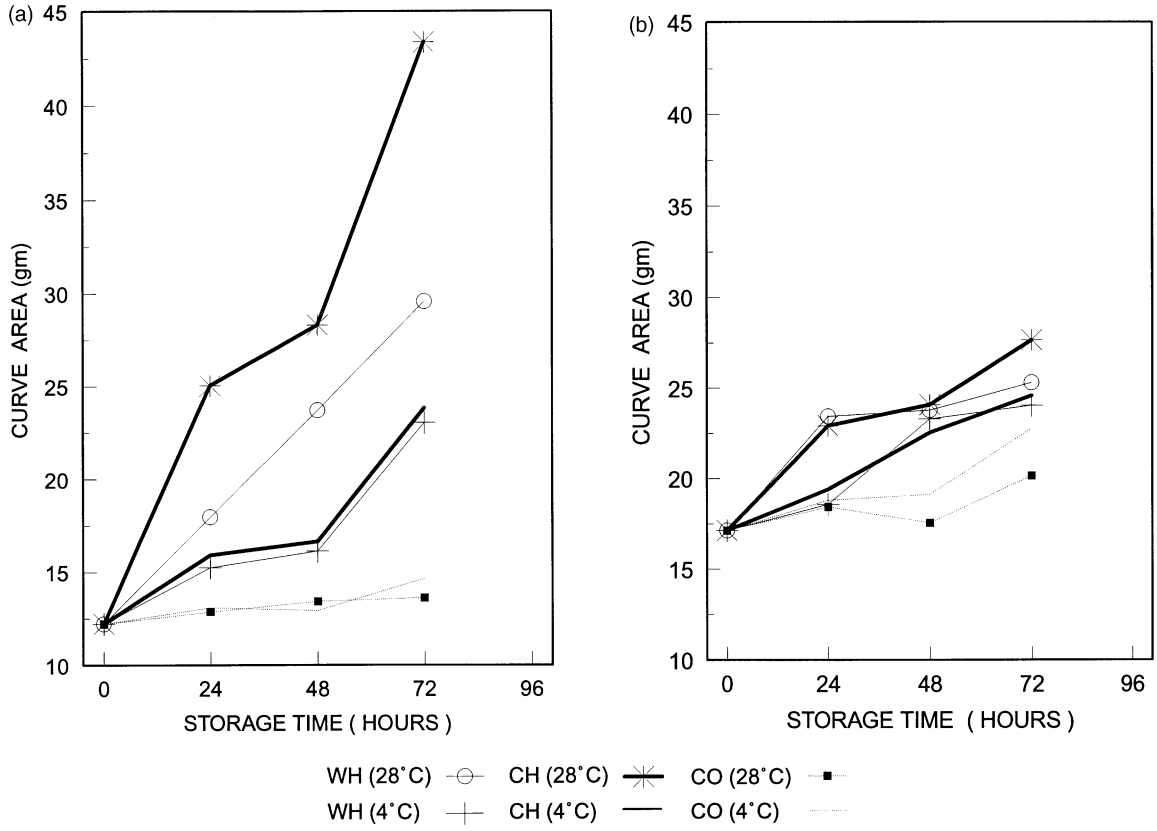

Fig. 11. Changes in curve areas (adhesiveness) of white (a) and yellow (b) cultivars of trifoliate yam tubers during storage.

as compared to the tubers stored under tropical ambient conditions. This suggests that the hardening of *D. dumetorum* tubers after harvest is temperature-dependent and that low temperature storage can be used to effectively delay the onset of hardening after harvesting.

Consistent increases in the peak force (hardness) during storage resulted from the rapid hardening of *D. dumetorum* tubers after harvesting, attributable to increases in cell wall stiffness and subsequent strengthening of cell wall bondings during storage of the tubers. Analysis of variance indicated that the sample treatment, cultivar, storage condition and storage time all significantly affected ($P \leqslant 0.05$) the hardness (peak forces) and curve areas of the tuber during storage (Table 3).

Table 3
F-values of process variables for hardness (peak force) and curve areas of *Dioscorea dumetorum* tubers

Process variables	Hardness (Peak force)	Curve area
Cultivar	3.828*	5.608*
Tuber treatment	9.874*	9.532*
Storage condition	10.259*	5.098*
Storage time	7.625*	11.997*

* Significant at $P \leqslant 0.05$.

3.2.1. Correlation between hardness (peak force) and the biochemical constituents of D. dumetorum tubers during storage

These were very high correlation coefficients between peak force (hardness) and all the biochemical constituents investigated, for both the white and yellow cultivars (Table 4). Very high negative correlation coefficients were found between hardness and moisture of the tubers and these ranged from $r = -0.9717$ to -0.9876, $P \leqslant 0.05$ for the white and yellow cultivars, respectively. Similarly, starch correlated negatively with

Table 4
Correlation between hardness (peak force) and the biochemical characteristics of *Dioscorea dumetorum* tubers

	Hardness (Peak force)	
	White	Yellow
Moisture	−0.9717*	−0.9876*
Starch	−0.9503*	−0.4872
Total alcohol-soluble sugars	0.9865*	0.9110*
Reducing sugars	0.9913*	0.8410*
Acid detergent fibre	0.9821*	0.9188*
Neutral detergent fibre	0.9662*	0.9259*
Lignin	0.9883*	0.3560
Cellulose	0.9752*	0.9380*
Hemicellulose	0.9506*	0.8680*

* Significant at $P \leqslant 0.05$.

ranges from $r = -0.4872$ to -0.9503. This means that the moisture and starch contents of the tuber are inversely related to the hardening phenomenon occurring in the tubers after harvesting. Therefore, increasing hardness levels have a reducing effect on the moisture and starch contents of the tubers during storage. However, all the plant cell wall polysaccharide constituents studied showed very high positive correlations with hardness of the tuber after harvest (Table 4). This indicates that the plant cell wall polysaccharide components of the *D. dumetorum* tubers influence the hardening phenomenon that occurs in the tubers after harvesting and therefore the increases observed in the cell wall polysaccharide components might be the major factors leading to the hardening of the tubers after harvest.

3.3. Hypothesis for the hardening mechanism

The hardening of *D. dumetorum* tubers during storage seems to be brought about by a series of biochemical reactions that occur in the tubers immediately after harvest, leading to changes in textural properties of the

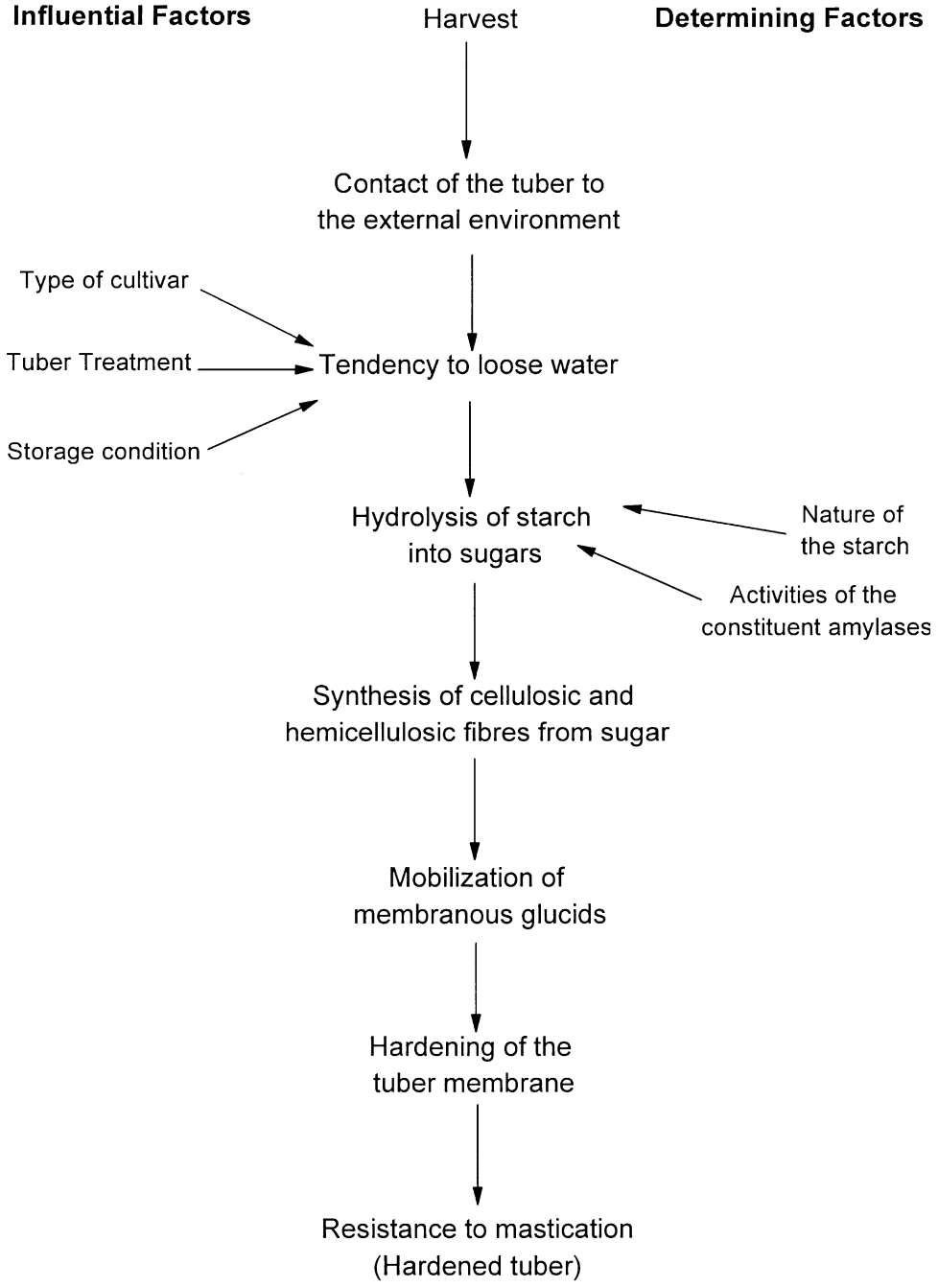

Fig. 12. Mechanism of the hardening phenomenon in *Dioscorea dumetorum* tubers after harvest.

tubers. Moisture and starch contents decreased to varying degrees, depending upon the cultivar, tuber treatment, storage time and conditions of storage. These probably resulted from the high tendency of the tubers to lose moisture to their external environment. Consequently, increasing levels of sugars (total alcohol-soluble sugars, reducing sugars and sucrose) as well as the plant cell wall polysaccharide components, comprising neutral detergent fibre and acid detergent fibre, were observed during storage of the tubers. This was reflected in the biochemical composition by increases in various cell wall constituents (cellulose, hemicellulose and lignin) during storage, rapid lignification and thickening of the cell walls of the tubers after harvesting. These changes may lead to the hardening the tuber membranes, as revealed by microstructural studies reported by Afoakwa and Sefa-Dedeh (2002). Based on these observations, a hypothesis for the hardening mechanism has been proposed as follows;

1. The cultivar, treatment given to the tuber after harvest and the post-harvest storage condition all influence the hardening process.
2. Physiological changes occur in the tubers after harvest, due to loss of moisture to the external environment, causing the tuber to harden.
3. Biochemical reactions involving the hydrolysis of starch into sugars occur, due the action of constituent amylases in the tuber.
4. Synthesis, of cellulosic and hemicellolosic fibres from sugars, leads to lignification and thickening of the cell walls.
5. Mobilization of membranous carbohydrates takes place by the process of epimerization of sugar units into cell wall matrices, causing the cell walls to thicken and consequently leads to the hardening of the tubers after harvest.

The proposed mechanism for the hardening phenomenon in the *D. dumetorum* tubers is shown in Fig. 12.

4. Conclusions

D. dumetorum tubers undergo physical and chemical changes, leading to the post-harvest hardening of the tubers after harvest. Moisture and starch contents decrease to varying degrees depending on the species and storage conditions. However, the levels of sugars and fibres and changes in textural properties increased with storage time. This is reflected in the biochemical composition by increases in the various contents of membranous carbohydrates (cellulose, hemicellulose and lignin) during storage. The hardening of the tubers after harvest is a physiological problem, brought about by a series of biochemical reactions occurring in the tubers after harvesting. Cutting tubers into pieces before storage increases the hardening process as compared to whole tubers. This means that increasing the surface exposure of the tubers to the external environment enhances their hardening process. No significant changes occur in the cooked tubers during storage. Very high correlations exist between hardness (peak force) and the biochemical characteristics of the tubers. Low temperature storage conditions (4–5 °C) effectively reduce the rate of biochemical and textural changes. Therefore, low temperature conditions (4–5 °C) are important for the effective storage of trifoliate yam tubers after harvesting.

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