ELSEVIER

PII: S0308-8146(97)00035-6

Food Chemistry, Vol. 60, No. 4, pp. 573–580, 1997

0308-8146/97 $17.00+0.00

Influence of withering, including leaf handling, on the manufacturing and quality of black teas — a review

K. I. Tomlins & A. Mashingaidze

Tea Research Foundation (Central Africa), P.O. Box 51, Mulanje, Malawi

(Received 12 January 1996; revised version received 20 December 1966; accepted 20 December 1996)

Literature on the influence of withering on maceration, fermentation and drying and on black tea quality is reviewed. The importance of including the handling of the leaf in the field and during transportation as an integral part of withering is stressed. The influence of physical and chemical changes in the green leaf, during withering, on the quality of black teas is discussed. Withering practices vary with climate, producing region, the type of manufacturing process and demands by the markets. Mechanised withering may improve quality by reduced handling of the leaf. The influence of plucking standards on withering and the effect of withering on the storage of tea are discussed. © 1997 Elsevier Science Ltd

INTRODUCTION

Black tea is manufactured in four distinct stages; withering, maceration or rolling, fermentation and drying (firing). Withering refers to the changes that occur in the green leaf from the time it is detached from the plant (plucked) to the time of maceration (Owuor & Orchard, 1989; Orchard, 1991). With improvements in tea manufacturing technology, the method and value of withering in relation to black tea quality appears to be changing. For the production of flavoury teas (Dev Choudhury & Bajaj, 1980*a*), where the tea is rolled, withering is considered vital for quality. In the production of plain teas, such as those manufactured in Kenya (Owuor & Orchard, 1989; Orchard, 1991) and Malawi (Hilton, 1975), the role of withering is less clear; some manufacturers now omit the factory withering stage altogether.

An aspect of withering that is now considered to be important is field withering, or leaf handling. Recent work in Malawi (Burton, 1995; Wilkie, 1995) suggests that up to 25% of the market value of tea can be lost before green leaf arrives at the factory door if it is poorly handled whilst in the field and during transit.

This paper reviews the physical and chemical transformations during withering and the implication of these changes on subsequent manufacturing stages and on the overall quality of tea.

Technical aspects of withering and their effect on subsequent stages of manufacture

Withering of green leaf in a tea factory has much to do with the technical difficulties in handling wet or over dry leaf during maceration, fermentation and drying.

Maceration

Fresh green leaf arriving at the factory typically has a moisture content above 75% on a wet basis and can be as high as 83%. Maceration machines operate most effectively within a fairly narrow green-leaf moisture range (68 to 72% on a wet basis; Hampton, 1992) and hence some moisture must usually be lost during withering. For Lawrie tea processor (LTP) maceration, a target moisture content on a wet basis of 71 to 72% is considered desirable (Johnson, 1990; Hampton, 1992). Cut-tear-curl (CTC) maceration can operate over a wider range of moistures, 68 to 72% being preferred (Choudhury, 1970; Hamilton, 1992). It is thought that excessive moisture in the green leaf will clog both the rotorvane and CTC rollers (Owuor *et al.*, 1987). The orthodox method utilises leaf at 60 to 66% (Choudhury, 1970; Hampton, 1992) (although it is not clear whether the moisture loss refers to per cent moisture content on a wet basis or a percentage of the original leaf weight). This is to ensure that the leaves are sufficiently flaccid for the rollers to produce the desired twist in the leaf. The Legg cutter (Johnson, 1990) is not dependent on the leaf moisture for efficiency of cutting but seems to have a reputation for producing 'brassy' teas, although Trinick (1962) reported an improvement in quality. Some authors report the degree of wither as per cent moisture content and others as percentage wither. These are not the same; moisture content refers to the per cent of moisture in the leaf on a wet basis, whereas percentage wither refers to weight loss in relation to the fresh weight.

Fermentation

Excessive moisture in the dhool may hinder aeration and temperature control resulting in uneven fermentation (Sanderson & Graham, 1973). Excessive withering may concentrate the catechins to levels that inhibit polyphenol oxidase (PPO) activity and reduce the expression of the cell contents onto the surface of the macerated leaf (Robertson, 1992). Hence, a significant proportion of the fermentation may occur within the leaf particle under limiting oxygen conditions. Moisture loss during withering does not appear to alter the optimum fermentation time (Ullah *et al.*, 1984; Owuor & Obanda, 1992*a*).

Drying

Dhool that is too wet has been reported to be difficult to dry evenly because it can form clumps, particularly in fluidised bed dryers (Owuor & Orchard, 1991, 1992).

Withering processes occurring in the green leaf

During withering, two processes occur in the green leaf. On the one hand, they are physical, leading to a loss in moisture and changes in cell membrane permeability (Sanderson, 1964) and, on the other, they are chemical, influencing the formation of the tea aroma, which is important for flavoury teas (Bhatia, 1962; Sanderson, 1964; Yamanishi *et al.*, 1966; Saijo & Takeo, 1973; Selvendran *et al.*, 1978; Wright & Fishwick, 1979; Dev Choudhury & Bajaj, 1980*a,b* Takeo, 1984*a*; Owuor *et al.*, 1986; Robinson & Owuor, 1992).

In practice, several withering methods have been described. A normal wither refers to the traditional method of withering where air is blown through the leaf (12 to 24 h) until the desired moisture loss is reached. Moisture is lost during the wither along with biochemical changes in the leaf. Heat may be applied on wet and humid days to remove moisture from the leaf.

A physical wither refers to a loss in moisture and changes in cell membrane permeability which result in the leaf becoming flaccid. It is achieved by passing air (ambient or heated) through the leaf. The physical wither can take about 4 h when ambient air is used. Shorter times of 2 to 2.5 h are possible with heated air.

Chemical wither refers to natural biochemical changes that occur inside the leaf. It is achieved by blowing air either intermittently or continuously at low flow rates through the leaf to keep it cool without losing moisture for between 4 and 18 h.

Two-stage withers relate to a chemical wither, used to store or hold the leaf, followed by a physical wither to lose moisture. The depth of the leaf bed may be greater than that used in troughs; the term tank-withering has been used for the chemical stage. A nil wither is when the green leaf is manufactured fresh.

The influence of the type of wither on made tea quality seems to differ between producing countries. For plain teas, such as those produced in Malawi and Kenya, tasters preferred teas that had been physically withered (Hilton, 1975; Owuor *et al.*, 1989; Orchard, 1991; Owuor & Orchard, 1991, 1992). In Kenya, the duration of chemical wither (0 to 18 h) did not have any effect on quality. In other producing regions such as Assam (Ullah, 1988), the chemical wither was necessary for producing full and round liquors and the duration could be reduced to 6 to 8 h by holding the leaf at elevated temperatures between 30 and 37°C and passing air through at a rate of $0.6\,m^3\,min^{-1}$. It has been reported that the withering time was not critical for teas lacking quality but should be shorter for quality teas (Keegal, 1950). Some manufacturers practise a two-stage wither (Owuor & Orchard, 1989; Orchard, 1991) which starts with a chemical wither in which the leaf is stored, followed by a short physical wither to lose moisture. Other manufacturers follow a nil wither (Orchard, 1991), since reasonable quality teas can be produced by a chemical wither alone (Ullah, 1984*a,b*; Owuor *et al.*, 1989)

Changes occurring in the green leaf during the physical wither

Immediately after plucking, the fresh leaf starts to lose water vapour. As withering progresses, the stomata of the lower leaf surface begin to close; two and a half times as much water is lost through the lower surface, which has stomata, compared to the upper surface which has no stomata (Orchard, 1991; Kramer & Kozlowski, 1979). The maximum initial drying rate is 0.075 kg of water per kg of green leaf per h (Johnson, 1990). As the degree of wither progresses, the permeability of the cell membranes in tea shoots increases. It has been noted that chilling of the leaf to 10°C or below increases cell permeability, whereas no change was recorded above 31°C (Sanderson, 1964). It has been estimated that, in addition to moisture loss, up to 4% of the dry matter in the leaf is lost as carbon dioxide through respiration (Roberts, 1948; Hampton, 1992).

To ensure good quality tea, an even wither is critical (Keegal, 1950). The rate of loss of moisture and temperature of the leaf during withering is related to surface moisture, humidity of the air, altitude, dry-bulb and wet-bulb temperature, air flow, packing density and whether heat is applied during withering (Johnson, 1987, 1990; Hampton, 1992). In compacted leaf, temperature rises of 3°C per h can occur, but the effect on quality is not known, although regular turning of the leaf was recommended (Johnson, 1990).

Biochemical changes in the green leaf during withering

A large number of chemical changes occur during withering (Dev Choudhury & Bajaj, 1980*a*; Agarwal, 1989). At the time of plucking, numerous biochemical and physiological processes occur in the green leaf. During manufacture, many of these processes will be altered and new processes commence. The known biochemical changes involved are the breakdown of proteins into amino acids, a decrease in lipids and fatty acids, carotenoids and chlorophylls, an increase in caffeine content and changes in sugars, organic acids, PPO activity and aroma-volatile components.

Proteins and amino acids

Protein levels are reduced by approximately 1.2% during withering and the changes accompany increases in amino acids which are thought to be involved in aroma formation (Bhatia, 1962, 1965; Roberts & Sanderson, 1966; Perera & Wickremasinghe, 1972; Saijo, 1973; Motoda, 1979; Dev Choudhury & Bajaj, 1980*a*). The increase in amino acids is thought to be because of the breakdown of protein by peptidase (Dev Choudhury & Bajaj, 1980*b*), although other routes may be involved since simple sugars formed during withering react with amino acids (Dev Choudhury & Bajaj, 1979). Some amino acids (glycine, alanine, valine, leucine, isoleucine and methione) form the corresponding Strecker aldehydes (formaldehyde, acetaldehyde, isobutryaldehyde, isovaleraldedhyde, 2-methylbutanal, methional) during fermentation (Sanderson & Graham, 1973). Such aldehydes can be further reduced to alcohols. These compounds are thought to cause poor flavour in tea (Owuor *et al.*, 1987, 1989). Other amino acids, for example phenylalanine, increase during withering to form phenylacetaldehyde, which can also be reduced to alcohols (Sanderson & Graham, 1973). These compounds can improve the tea aroma (Owuor *et al.*, 1987, 1989).

The influence of withering on the amino acid composition varies with the duration, ambient temperature and moisture. Withers of short duration have little effect on amino acid composition, whereas longer withers allow for a build-up of amino acids. When moisture loss was prevented, amino acid formation was reduced. The formation of amino acids was reduced at temperatures below 18°C and accelerated as the temperature increased to 40°C; formation stopped after 6 h because of the death of the tissues (Roberts & Sanderson, 1966).

Carbohydrates and simple sugars

Simple sugars increase during withering, accompanied by a decrease in total carbohydrates (Roberts, 1962; Dev Choudhury & Bajaj, 1980*a*). Sugars react with amino acids in the formation of aroma compounds (Dev Choudhury & Bajaj, 1979).

Lipids and fatty acids

Lipids are important in the development of aroma compounds in black tea. The levels of saturated fatty acids (FA) decrease during withering, but their influence on black tea flavour is not known (Selvendran *et al.*, 1978; Wright & Fishwick, 1979). More is known about the role of unsaturated FA during withering and their influence on black tea quality. During withering, lipid degradation occurs and the unsaturated FA decrease to undergo regio- and enantio-selective oxidative cleavage to form aroma compounds (Wright & Fishwick, 1979; Hatanaka *et al.*, 1984; Owuor *et al.*, 1987, 1989). Aroma compounds formed from unsaturated FA breakdown are thought to have a negative effect on flavour. The strong grassy odour from the withering troughs is a result of aroma compounds produced from FA (Takeo & Tsushida, 1980; Hatanaka *et al.*, 1984). The breakdown of unsaturated FA during withering is catalysed by lipoxygenase which increases in activity during withering (Takeo & Tsushida, 1980).

Carotenoids

The degradation of carotenoids during withering and fermentation leads to important flavour in high quality tea compounds (Trimanna & Wickremasinghe, 1965; Sanderson *et al.*, 1971; Renold *et al.*, 1974; Dev Choudhury & Bajaj, 1980*b*; Hazarika & Mahanta, 1983). Carotenoids and chlorophylls have been identified as important for quality in Kenyan teas and have been suggested as the basis of predicting quality (Taylor & McDowell, 1991; Taylor *et al.*, 1992). Carotenoids (violoxanthin and neoxanthin) are significantly reduced during withering (Hazarika & Mahanta, 1983) whereas β-carotene and lutein only decline during fermentation. The decline in carotenoid concentration is most significant during physical (not chemical) wither.

Chlorophyll

Teas with high chlorophyll contents normally result in inferior liquors. It is thought that the conversion of chlorophylls to pheophytins during fermentation and firing contributes to black tea appearance (Dev Choudhury & Bajaj, 1980*b*; Taylor *et al.*, 1992). During withering, the level of chlorophylls declines by 15%, forming chlorophyllides. It has been noted that green leaf high in chlorophyll produces tea with a grassy odour, but the cause of the grassy odour has not been identified (Nikolaishvilli & Adeishvilli, 1966; Wickremasinghe & Perera, 1966; Dev Choudhury & Bajaj, 1980*b*).

Caffeine

Teas with low levels of caffeine or those containing poorly fermented leaf particles lack the ability to cream (Roberts, 1963; Bhatia, 1964; Dev Choudhury & Bajaj, 1980*a*). The creaming properties of made tea are adversely affected by insufficient wither. Caffeine increases during withering (Bhatia, 1962; Sanderson & Graham, 1973; Dev Choudhury & Bajaj, 1980*a*; Owuor *et al.*, 1986, 1989; Bhuyan & Mahanta, 1989) but is reduced when tea is withered at a higher temperature of 38°C (Dev Choudhury & Bajaj, 1980*a*). The increase in caffeine concentration appears to be related to amino acid metabolism (Roberts & Sanderson 1966). The method of withering may influence the caffeine concentration since, compared to normal withers, the level in physically withered teas was less (Owuor *et al.*, 1987).

Catechins and enzyme activity

The total catechin content decreases during withering (Hilton, 1975; Bokuchava & Skobeleva, 1980). Epigallocatechin (EGC), gallocatechin (GC), epigallocatechin gallate (EGCG) and epicatechin gallate (ECG) decrease in amount during withering, whilst epicatechin (EC) increases. Catechins produce theaflavin (TF) and low molecular weight, chromatographically-resolved thearubigins (TR) in the presence of PPO (Opie *et al.*, 1990; Robertson, 1992). In the presence of peroxidases (PO), unresolved, high molecular weight TRs are formed (Finger, 1994). The activity of PPO has been reported to decrease during withering (Hilton, 1975; Ullah & Roy, 1982; Ullah, 1984*a,b;* Ullah *et al.*, 1984; Robertson, 1992) as a result of moisture loss. In India, the method of withering appeared to have little effect on either PPO or PO activity (Mahanta *et al.*, 1993). The activity of PPO was restored when the withered leaf was rehydrated (Ullah & Roy, 1982). The activity of the enzyme is also reduced by increased temperature (Cloughley, 1979). Losses in activity of 70% were noted at temperatures of 35°C which varied greatly between clones.

Non-enzymic chemical oxidation of the catechins may occur during the fermentation stage (Bailey *et al.*, 1993) and is thought to produce pigments similar to TR in black tea. The occurrence and influence of non-enzymic changes during withering is not known.

Influence of withering on the fermentation process

Withering can influence the formation of black tea phenolics and volatile compounds during fermentation.

Black tea phenolics

Unwithered leaf is associated with teas that are bright, brisk, but thin; correspondingly, the teas were higher in TF but lower in TR (Ullah *et al.*, 1984; Owuor & Orchard, 1989; Orchard, 1991). Harder withers produced teas with less brightness and briskness, but improved body; the TFs were lower and the TRs higher (Perera & Wickremasinghe, 1972; Ullah, 1984*a,b*; Owuor *et al.*, 1986, 1987, 1989). Leaf withered to different moisture levels in Malawi (Mashingaidze, 1995) showed that TF levels declined by 16% as the moisture in the leaf decreased from 72.5 to 64.8%. There was no difference in the tasters' market evaluation. It is thought that high leaf-moisture contents are associated with high PPO activity, which enhances the formation of TFs and hinders the formation of TRs (Hazarika *et al.*, 1984).

A biphasic production of TFs during withering has been noted and is thought to be the result of different phases in enzyme activity (Obanda & Owuor, 1991; Kumsinda, 1993; Madanhire, 1993). Teas manufactured during the initial rise in TF concentration were bright but thin compared to those manufactured after the second increase in TF.

Volatile compounds

Withering is thought to improve the aroma of tea (Yamanishi *et al.*, 1966; Saijo & Takeo, 1973; Saijo, 1977; Takeo & Mahanta, 1983; Takeo, 1984; Owuor *et al.*, 1987; Mahanta & Boruah, 1989; Owuor *et al.*, 1989) and affect the volatile composition (Takeo, 1984*a*). Studies in India (Mahanta & Boruah, 1989) indicate that withering influences the development of terpenoids, improving the flavour of tea. Flavour compounds that are important to quality (linalool, geraniol, methylsalicylate) have been reported to increase during withering, while compounds (E-2-hexenal) detrimental to quality are highest in unwithered teas (Yamanishi, 1967; Howard, 1978). Groups I and II volatile flavour compounds (VFC) impart an inferior, grassy aroma and a sweet flowery aroma to black tea, respectively (Owuor & Orchard, 1992). During chemical withering, both groups I and II declined in Kenya teas, although group I declined faster, resulting in an improvement in quality.

For oolong teas (Takeo, 1984*a*), it has been noted that volatile compounds increased in warm withered leaves at near 40°C during the first stage of withering. Furthermore, the production of aroma compounds was accelerated by soft hand-rolling every half hour during the withering process. Withering under direct sunlight or artificial light also improved the aroma.

Leaf handling from the field to the factory

The green leaf starts the withering process from the moment it is plucked from the tea bush. However, little has been published on the effect that handling of the leaf, from the time it is plucked to the time that it arrives at the factory, has on market value or subsequent stages in manufacture. Initial work in Malawi (Hilton, 1975) suggested that handling of clonal leaf (SFS204) did not adversely affect quality, which was still of a better quality than Indian hybrid seedling tea. Overheating of the leaf was thought to cause more quality loss than physical leaf damage (bending, bruising and tearing).

Poorly-handled leaf, that has undergone senescence, will turn red. This is thought to occur when green-coloured chloroplasts are transformed into red-coloured chromoplasts. Studies in Kenya (Melican & Mallows, 1992) indicated that red leaf formation occurred in 30 min when buds were exposed to a temperature of 45°C. For the first and second leaves, red leaf occurred after 40 and 165 min, respectively. Tea made from the red leaf was found to have lower TFs but higher TRs than a control sample. Tasters scored tea made from red leaf as too poor to rate. In Papua, New Guinea, an inclusion of 10% red leaf resulted in a perceivable reduction in quality (Melican & Mallows, 1992).

Field withering in Malawi and its influence on market value of made tea

Recently, a study was carried out in Malawi (Burton, 1995) which, although not done in depth, was wide-ranging. It indicated that up to 25% of the value of tea could be lost before the leaf arrived at the factory. The study comprised a field survey, monitoring green-leaf temperature, duration of storage in sacks, packing density, sack design and green-leaf condition, and their effects on made tea quality.

Field survey

A field survey indicated that leaf took up to 10 h to reach the factory and, in that time, became heated to temperatures between 25 and 49°C. The method of transport could affect the time that the leaf remained in the field, open trailers being easier to load and unload than pew-type trailers. The design of shelters may also have an effect on leaf temperature, permanent bamboo-type shelters recording lower average maximum ambient temperatures of 29°C compared with those of portable hessian bag shelters at 35°C.

Temperature, time and tea variety

The rise in leaf temperature in the field varied with the variety of leaf and the ambient temperature. Most (70%) of the rise in temperature occurred under the shelters. The temperature of clonal leaf appeared to rise more rapidly than Indian hybrid. Most of the increase in temperature occurred in the first 6 h, particularly when the ambient temperature was above 30°C. For clonal leaf, there were signs of red leaf at temperatures at or above 35°C when stored for more than 6 h. The highest leaf temperature recorded was 52°C. The loss in value and TF accelerated with increasing temperature. A 23% loss in valuation was noted when the leaf temperature reached 45°C after 9 h.

A study in Kenya (Owuor & Obanda, 1992*a*,*b*) on the influence of temperature on chemical withering also showed that holding the leaf at higher temperatures lowers black tea quality, reduces TF and increases TR.

Weight of green leaf (packing density) in sacks and sack design

The weight of green leaf (SFS204) stuffed into sacks influenced the rise in temperature. Although initially the rise in temperature was the same, regardless of packing density, after 2 h, the greater the weight of green leaf, the higher was the rise in temperature, which reached a maximum of 51°C. The tasters' evaluations indicated that packing a sack with 8 kg gave the highest score followed by open leaf, and packing at 12 kg came last. The design of the bag can also influence the quality of the leaf. Net bags, allowing more air to flow between the leaves, gave lower leaf temperatures and made-tea evaluations. The influence of bag design was both density- and time-related; for short storage periods, the design of the bag was less important, but for longer storage times the loss in quality for leaf stored in hessian bags was greater.

Leaf condition and made tea quality

Physical damage of the leaf can perhaps have the largest effect on made-tea quality. Brokers' evaluations showed that, after 9 h, tea manufactured from damaged green leaf (SFS204) was rated as dull and flat; scoring zero for briskness, one for brightness, and two for colour of infusion on a zero to ten scale. The market value of the damaged leaf was between 11 and 16% less than undamaged leaf. In other studies (Saijo, 1977), aliphatic, aromatic and terpenoid alcohols increased in damaged leaf during withering. In particular, linalool oxide and geraniol, which enhance tea flavour, increased markedly before a slight decrease. However, the effect on quality as determined by tasters was not reported.

Influence of other factors

The standard of plucking can have an effect on withering. How the leaf is withered can influence the quality of made tea during storage and its packing density.

Plucking standards and factory withering

A study in Kenya of the influence of plucking standards on withering (Obanda & Owuor, 1994) showed that quality, as perceived by tasters, declined with coarser plucking standards and that the decline was least when a chemical wither was employed. Biochemical analysis showed that TRs increased with a coarse plucking standard and that the increase was greatest for normal withers. TFs decreased with coarser plucking standards, but the decline was least with chemical withering. PPO activity was highest with the chemical wither. The flavour index declined with plucking standard.

Storage of made tea

Made tea manufactured in Malawi from leaf that had been withered for more than 10 h had improved keeping properties with respect to TF composition (Cloughley, 1981). Tea manufactured from shorter withers had the highest initial TF values but deteriorated more rapidly. A study in Kenya (Owuor & Obanda, 1992*c*) found similar results.

Packing density of made tea

Studies in Kenya have shown that chemical withers tend to produce teas of lower density, but acceptable quality (Orchard, 1991). However, the lower density leads to higher storage and transportation costs (Owuor & Obanda, 1993).

Mechanisation of leaf handling and withering

In factory withering, the green leaf is usually transferred to jats or withering troughs manually. This is labour-intensive and can increase the handling of the leaf. Withering has been mechanised in a factory in Kenya (Wemyss, 1973) and one in Assam (Boruah, 1988). Such systems are reported to reduce labour costs and improve quality through reduced handling of the green leaf.

A machine has been developed to remove water adhering to leaves before plucking (Watanbe *et al.*, 1983). It uses a fan and rotary sponge brushes to remove excess water. With an air speed of $40\,m\,s^{-1}$ for the fan, most of the adhering water was removed and the remainder evaporated within 10 min. No injury to the leaf was observed, but the influence on quality was not reported.

CONCLUSIONS

While much has been reported on changes occurring in the leaf whilst withering in the factory, until recently little was known about the importance of changes that occur in the field and how these might influence subsequent stages in the manufacturing process. For plain teas, such as those manufactured in Malawi, it is now clear that much of the potential value of the tea can be lost before the leaf has arrived at the factory. Also, little is known about the influence of poor leaf handling on the quality of plain and flavoury teas manufactured in other producing regions, or how it might affect the withering and fermentation of tea. For example, should leaf that has been in the field for 10 h and attained temperatures in excess of 40°C be treated in the factory in the same way as fresh leaf?

Withering involves both physical and chemical changes in the green leaf. The physical changes, such as the rate of moisture loss, might be easily determined if the moisture content, mass of the fresh leaf, altitude and humidity are known and the air flow and any applied heat during withering can be closely controlled. Where space is important, costs may be reduced by utilising a two-stage withering system. While much is known about the biochemical changes that occur in the green leaf during withering, the tea manufacturers are still very dependent on tea tasters to assess quality. Rapid objective methods need to be devised to measure green leaf moisture content and when the desired chemical wither is attained.

Withering practices differ with country and the type of tea being manufactured. For plain teas such as those from southern Africa, moisture loss by a physical wither appears to be the most important for quality as perceived by tasters. For more flavoury teas, a chemical wither is considered important.

When comparing the literature on withering methods, it was noted that the conditions of experimentation were not reported consistently or were omitted. For example, the per cent wither might refer to the moisture content of the withered leaf on a wet or dry weight basis or the proportion of weight lost in relation to the original weight of fresh leaf. In this review, the moisture contents are reported as per cent moisture on a wet weight basis when this is known. Other parameters which should be reported to allow proper comparisons of withering methods to be made are the condition of the leaf, altitude, ambient air temperatures, humidity, airflow rate, including whether this was intermittent or continuous, when and how much heated air was applied, green-leaf bed loading on the withering trough (kg of green leaf per square metre), depth of leaf and how frequently the leaf was turned.

REFERENCES

Agarwal, B. (1989). Factors affecting quality of tea during processing. *S. L. J. Tea Sci.*, **58**, 64–72.

Bailey, R. G., Nursten, H. E. & McDowell, I. (1993). The chemical oxidation of catechins and other phenolics: A study of the formation of black tea pigments. *J. Sci. Food Agric.*, **63**, 455–464.

Bhatia, I. S (1962). Chemical aspects of withering. *Two and a Bud*, **9**, 26–30.

Bhatia, I. S. (1964). The role of chemistry in tea manufacture. *Two and a Bud*, **11**, 109–117.

Bhatia, I. S. (1965). Nitrogen metabolism of detached tea shoots. I. Changes in amino acids and amides of tea shoots during withering. *J. Sci., Food Agric.*, **16**, 759–769.

Bhuyan, L. P. & Mahanta, P. K. (1989). Studies on fatty acid composition in tea *Camellia sinensis*. *J. Sci. Food Agric.*, **46**, 325–330.

Bokuchava, M. A. & Skobeleva, N. I. (1980). The biochemistry and technology of tea manufacture. *CRC Critical Reviews, Food Sci. Nutrit*, 303–370.

Boruah, T. C. (1988). A package deal for withering. In *Tea Technology — Today and Tomorrow*, Proc. 30th Tocklai Conf. 1988, Tea Research Association, Assam, India, 114–122.

Burton, S. J. A. (1995). Leaf handling project, Part of B.Sc degree in Environmental Management, Silsoe College, Cranfield University, U.K.

Choudhury, R. (1970). Withering, Serial No 185, K2 file, November 1970, Tocklai Experimental Station, Assam, Indian.

Cloughley, J. B. (1979). The effect of temperature on enzyme activity during the fermentation phase of black tea manufacture. *J. Sci. Food Agric.*, **31**, 920–923.

Cloughley, J. B. (1981). Storage deterioration in Central African Tea: the effect of some production variables on theaflavin degradation. *J. Sci. Food Agric.*, **32**, 1229–1234.

Dev Choudhury, M. N. & Bajaj, K. L. (1979). Incorporation of 14C-compounds into amino acids and polyphenols of excised tea shoots. *Plant Biochem. J.*, **6**, 16–23.

Dev Choudhury, M. N. & Bajaj, K. L. (1980*a*). Biochemical changes during withering of tea shoots. *Two and a Bud*, **27**, 13–16.

Dev Choudhury, M. N. & Bajaj, K. L. 1980*b*). Role of chlorophylls, amino acids and sugars in tea. *Two and a Bud*, **27**, 16–20.

Finger, A. (1994). In-vitro studies on the effect of polyphenol oxidase and peroxidase on the formation of polyphenolic black tea constituents. *J. Sci. Food Agric.*, **66**, 293–305.

Hampton, M. G. (1992). Production of black tea. In *Tea—Cultivation to Consumption*, ed. K. C. Willson & M. N. Clifford. Chapman and Hall, London, pp. 459–511.

Hatanaka, A., Kajiwar, T. & Sekiya, J. (1984). Enzyme oxygenative cleavage reaction of linolenic acid in leaves, chloroplastic lipoxgenase and fatty acid hydroperoxidelyase in tea leaves. In *The Metabolism, Structure and Function of Plant Lipids*, ed. P. K. Stumpf, J. B. Mudd & W. D. Nes. Plenum Publishing Corporation, New York, pp. 391–398.

Hazarika, M. & Mahanta, P. K. (1983). Some studies on carotenoids and their degradation in black tea manufacture. *J. Sci. Food Agric.*, **34**, 1390–1396.

Hazarika, M., Sukhomoy, K., Chakravarty, K. & Mahanta, P. K. (1984). Studies on thearubigin pigments in black tea manufacturing systems. *J. Sci. Food Agric.*, **35**, 1208–1218.

Hilton, P. J. (1975). Manufacture of tea in Central Africa. Tea Research Foundation of Central Africa, Mulanje, Malawi.

Howard, G. E. (1978). The volatile constituents of tea. *Food Chem.*, **4**, 97–106.

Johnson, A. L. (1987). Some comments on withering. Tea Research Foundation (Central Africa), P.O. Box 51, Mulanje, Malawi (unpublished).

Johnson, A. L. (1990). Manufacture — Section 14, Tea Planters Handbook. Tea Research Foundation (Central Africa), P.O. Box 51, Mulanje, Malawi.

Keegal, E. L. (1950). Quick withering at high temperature. *TRIP Ceylon Bulletin*, **32**, 32–33.

Kramer, J. P. & Kozlowski, T. T. (1979). *Physiology of Woody Plants*. Academic Press, London, 787pp.

Kumsinda, A. (1993). Preliminary trails on the effect of chemical withering time. Tea Research Foundation (Central Africa), Malawi (unpublished).

Madanhire, J. (1993). The effect of short withers on the quality of made tea. Tea Research Foundation (Central Africa), Malawi (unpublished).

Mahanta, P. K. & Boruah, S. (1989). Relationship between process of withering and aroma characteristics of black tea. *J. Sci. Food Agric.*, **40**, 461–468.

Mahanta, P, K., Boruah, S. K., Boruah, H. K. & Kalita, J. N. (1993). Changes of polyphenol oxidase and peroxidase activities and pigment composition of some manufactured black teas (*Camellia sinensis* L.). *J. Agric Food Chem.*, **41**, 272–276.

Mashingaidze, A. (1995). Effect of different moisture contents at maceration on black tea quality. Proceedings of the first regional tea seminar, 22–23 March 1995, Blantyre, Malawi. ed. A. M. Whittle & F. R. B. Khumal, Tea Research Foundation, Malawi, pp. 133–135.

Melican, N. J. T. & Mallows, R. (1992). Occurrence and causes of red leaf in plucked tea before withering. Teacraft Technical Services Company, Bedford, UK.

Motoda, S. (1979). Formation of aldehydes from amino acids by polyphenol oxidase. *J. Ferment. Technol.*, **57**, 395–399.

Nikolaishvilli, D. K. & Adeishvilli, N. E. (1966). Chromatographic study of the quantitative changes in tea leaf pigments during production of black tea. *Byull Uses. Nauch, Iss. Ins Chai Pro.*, **2**, 50–60.

Obanda, M. and Owuor, P. O. (1991). Changes in the quality of black teas due to duration of chemical wither and type of drier in a large scale commercial factory. *Annual Report 1991*, pp. 141–148. Tea Research Foundation of Kenya, Kericho.

Obanda, M. & Owuor, P. O. (1994). Effects of wither and plucking methods on the biochemical and chemical parameters of selected Kenyan tea. *Discovery and Innovation*, **6**, 190–197.

Opie, S. C., Robertson, A. & Clifford, M. N. (1990). Black tea thearubigins — their HPLC separation and preparation during in-vitro oxidation. *J. Sci. Food Agric.*, **50**, 547–561.

Orchard, J. E. (1991). Technical Report 1988-91. ODA TCO, Tea Research Foundation of Kenya, P.O. Box 820, Kericho, Kenya, 126pp.

Owuor, P. O. & Obanda, M. (1992*a*). Effects of chemical wither temperatures on black tea quality. *Annual Report 1992*, p. 93. Tea Research Foundation of Kenya.

Owuor, P. O. & Obanda, M. (1992*b*). Effect of fermentation duration of leaf chemically withered at warm temperature, ambient temperature and mixture of the two on black tea quality. *Annual Report 1992*, pp. 93–96. Tea Research Foundation of Kenya.

Owuor, P. O. & Obanda, M. (1992*c*). Changes in tea quality due to degree of physical wither, fermentation time and post manufacture storage time (commercial factory). *Annual Report 1992*, pp. 86–89. Tea Research Foundation of Kenya.

Owuor, P. O. & Obanda, M. (1993). Effects of different processing methods on quality of black tea. *Annual Report 1993*, pp. 116–122. Tea Research Foundation of Kenya.

Owuor, P. O. & Orchard, J. E. (1989). Withering. *Annual Report 1989*, pp. 89–102. Tea Research Foundation of Kenya.

Owuor, P. O. & Orchard, J. E. (1991). Variations in black tea quality due to changing withering techniques in smallholder factories. *Tea*, **12**, 32–40.

Owuor, P. O. & Orchard, J. E. (1992). Effects of storage time in a two-stage withering process on the quality of seedling black tea. *Food Chem.*, **45**, 45–49.

Owuor, P. O, Reeves, S. G. & Wanyoko, J. K. (1986). Correlations of theaflavin contents and valuations of Kenyan black teas. *J. Sci. Food Agric.*, **37**, 507–513.

Owuor, P. O., Tsushida, T., Horita, H. & Murai, T. (1987). Effects of artificial withering on the chemical composition and quality of black tea. *Trop. Sci.*, **27**, 159–166.

Owuor, P. O, Wanjiera, J. O., Njeru, K. E., Munavu, R. M. & Bhatt, B. M. (1989). Comparison of chemical composition and quality changes due to different withering methods in black tea manufacture. *Trop. Sci.*, **29**, 207–213.

Perera, K. P. W. C. & Wickremasinghe, R. L. (1972). Properties of tea polyphenol oxidase. *Tea Quart.*, **43**, 153–163.

Renold, W., Nof-Muller, R., Keller, U., Willhalm, B. & Ohloff, C. (1974). An investigation of tea aroma. I. New volatile black tea constituents. *Helv. Cham. Acta.*, **57**, 1301–1308.

Roberts, E. A. H. (1948). Calculation of moisture content of withered leaf from percentage wither. Serial No. 19, K2 file, March 1948, Tocklai Experimental Station, Assam, India.

Roberts, E. A. H. (1962). The chemistry of tea manufacture. *J. Sci. Food Agric.*, **9**, 381–390.

Roberts, E. A. H. (1963). The phenolic substances of manufactured tea. X. The creaming down of tea liquors. *J. Sci. Food Agric.*, **14**, 700–705.

Roberts, G. R. & Sanderson, G. W. (1966). Changes undergone by the free amino acids during manufacture of black tea. *J. Sci. Food Agric.*, **17**, 182–188.

Robertson, A. (1992). The chemistry and biochemistry of black tea production—the non-volatiles. In *Tea—Cultivation to Consumption*, eds K. C. Willson & M. N. Clifford. Chapman and Hall, London, pp. 555–597.

Robinson, J. M. & Owuor, P. O. (1992). Tea Aroma. In *Tea—Cultivation to Consumption*, eds K. C. Willson & M. N. Clifford. Chapman and Hall, London, pp. 603–647.

Saijo, R. (1977). Mechanisms of developing black tea aroma with special reference to alcoholic compounds. *J. A. R. Q.*, **11**, 216–220.

Saijo, R. & Takeo, T. (1973). Volatile and non-volatile forms of aroma compounds in tea leaves and their changes due to injury. *Agric. Biol. Chem.*, **37**, 146–163.

Sanderson, G. W. (1964). The theory of withering in tea manufacture. *Tea Quart.*, **35**, 146–163.

Sanderson, G. W. & Graham, H. N. (1973). On the formation of black tea aroma. *J. Agric. Food Chem.*, **21**, 576–585.

Sanderson, G. W., Co, H. & Gonzalez, J. G. (1971). Biochemistry of tea fermentation: the role of carotenes in black tea aroma formation. *J. Food Sci.*, **36**, 231–236.

Selvendran, R. R., Reynolds, J. & Gilliard, T. (1978). Production of volatiles by degradation of lipids during manufacture of black tea. *Phytochem.*, **17**, 233–236.

Takeo, T. (1984*a*). Effect of the withering process on volatile compound formation during black tea manufacture. *J. Sci. Food Agric.*, **35**, 84–87.

Takeo, T. (1984*b*). Withering effect on the aroma formation found during oolong tea manufacture. *Agric. Biol. Chem.*, **48**, 1083–1085.

Takeo, T. & Mahanta, P. K. (1983). Why CTC tea is less fragrant. *Two and a Bud*, **30**, 76–77.

Takeo, T. & Tsushida, T. (1980). Changes in lipoxygenase activity in relation to lipid degradation in plucked tea shoots. *Phytochem.*, **19**, 2521–2522.

Taylor, S. J. & McDowell, I. J. (1991). Rapid classification by HPLC of plant pigments in fresh tea (*Camellia sinensis* L) leaf. *J. Sci. Food Agric.*, **57**, 287–291.

Taylor, S., Baker, D., Owuor, P., Orchard, J., Othieno, C. & Gay, C. (1992). A model for predicting black tea quality from the carotenoid and chlorophyll composition of fresh green tea leaf. *J. Sci. Food Agric.*, **58**, 185–191.

Trimanna, A. S. L. & Wickremasinghe, R. L. (1965). Studies on quality and flavour of tea. 2. The carotenoids. *Tea Quart.*, **3**, 115–121.

Trinick, J. M. (1962). Withering — its effect during manufacture and on made tea. *Two and a Bud*, **9**(2), 31–34.

Ullah, M. R. (1984*a*). A reappraisal of withering process in black tea manufacture. I. Physical and chemical withers and their effects on tea liquors. *Two and a Bud*, **31**, 20–24.

Ullah, M. R. (1984*b*). A reappraisal of withering process in black tea manufacture. II. Chemical wither in current practices of artificial withering and its effects on tea liquors. *Two and a Bud*, **31**, 24–27.

Ullah, M. R. (1985). Lowering of enzyme activity of tea leaf on storage and its effects on quality of made teas. *Two and a Bud*, **32**, 53–56.

Ullah, M. R. & Roy, P. C. (1982). Effect of withering on the polyphenol oxidase level in the leaf. *J. Sci. Food Agric.*, **33**, 492–495.

Ullah, M. R., Gogoi, N. & Boruah, D. (1984). The effect of withering on fermentation of tea leaf and development of liquor characters of black teas. *J. Sci. Food Agric.*, **33**, 1142–1147.

Watanbe, I, S., Saigo, T. & Nakano, T. (1983). Improvement of tea quality by the management of wet leaves. I. Development and field trial of an experimental machine for removing water adhering to tea leaves. *Res. Bull. Aichi Ken Agric. Res. Centre*, **15**, 145–150.

Wemyss, A. (1973). Mechanical loading of withering troughs. *World Crops*, **25**, 314–316.

Wickremasinghe, R. L. & Peresa, U. H. (1966). The blackness of tea and colour of tip. *Tea Quart.*, **37**, 232–235.

Wilkie, A. S. (1995). Leaf handling study. *TRF QNL*, **120**, 26–38.

Wright, A. J. & Fishwick, M. J. (1979). Lipid degradation during manufacture of black tea. *Phytochem.*, **18**, 1511–1513.

Yamanishi, T. (1967). Flavour of black tea. *Japan Agric. Res. Quart.*, **2**, 25–32.

Yamanishi, T., Kobayashi, A., Sata, H., Nakanura, H., Oswa, K., Uchida, A., Mori, S. & Saijo, R. (1966). Flavour of black tea. Part IV. Changes in flavour constituents during the manufacture of black tea. *Agric. Biol. Chem.*, **30**, 784–792.