Summary of Coffee Technical Literature Regarding Green Bean Moisture and Color

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While coffee is at its most stable in the green form, flavor loss and changes do occur over time. These are of interest to both roasters, who must deal with the changes in green coffee quality, and purveyors of green coffee, who must manage the storage conditions of green coffee to maintain maximum value. This paper does not contain any new experimental information, but is a summary of current scientific literature on the green coffee storage and transport. The major effects upon green coffee during these periods are relative humidity, moisture content, temperature, and gas composition.

Physical Properties of Green Coffee

The physical properties of green coffee include density, porosity, total moisture (MC), and water activity (A_w). When green coffee reaches a moisture level of 30% or below (including the 10-12% moisture at which the coffee is shipped), it becomes hygroscopic, meaning it readily absorbs moisture from the air except under conditions of equilibrium. Equilibrium refers to the “moisture balance” between environment and bean: environmental humidity and temperature balanced with the moisture in the coffee in which no change is taking place. A major goal of controlling conditions of green coffee storage and/or packaging is to maintain the coffee as close to equilibrium as possible (a “steady state”) over time and under different anticipated conditions.

Density is the ratio of mass to volume; for example, any metal is denser than Styrofoam. The “bulk density” of coffee is measured by filling a cylinder known volume with coffee beans. Measurement of “absolute density” also takes into account the gaps between beans by filling the cylinder containing the coffee with a liquid of known weight to fill in the gaps (soybean oil is recommended), re-measuring, and subtracting the difference from the original measurement. The absolute density of green coffee is between 1.25-1.30 g/ml.

Porosity refers to the gaps between the beans that allow air to pass through. These factors have an influence on moisture exchange, either in drying through heat and air movement or in absorbing moisture.

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3 Rojas, “Green Coffee Storage”, p. 734
Total moisture (MC, “moisture content”) is the amount of H2O by weight that is contained within the green bean. For export, green coffee moisture must be lowered to a maximum of 12% and will remain at this level at a humidity of between 60-65%. In more humid areas, coffee may be dried to 10-11% to increase storage time, while in other areas drying is stopped at 13-14% since some moisture will be lost during hulling\(^5\). These measurements refer to the average moisture content of the sample being tested; a moisture content of 12% may indicate moisture levels of individual beans ranging from 9 to 15\(^6\). It may be necessary to take several random pinch-samples to precisely determine the moisture content.

*Water activity (Aw):* Water activity is defined as the “equilibrium property of water at a given temperature and moisture content\(^*\). It is measured as the ratio of the water vapor pressure over a sample (p, for pressure; a measurement taken at the surface of the bean) to that over pure water (p0) at the same temperature: \(A_w = \frac{p}{p_0}\)^8.

Water activity characterizes the thermodynamic potential of the moisture in a substance and its measurement is used to predict changes in substance properties. It is used in foods as a measure of potential degradation, which can be due to internal chemical changes or becoming a substrate for living organisms such as molds, bacteria, or yeasts. As a thermodynamic measurement, an important component of the measurement is the temperature (heat) of the system.

The study of thermodynamics deals with large systems (such as a mass of green coffee) and how they exchange heat and other energy, such as pressure. The internal energy of the system based on its temperature, volume, and pressure is called its enthalpy, also called its thermodynamic potential.

Heat energy is measured in terms of Joules (J); it takes 4.185 J to raise 1 g of water 1º C. The application of heat (or other energy) to a system results in work done (such as chemical changes or movement of substances) or storage of the energy internally. The specific heat of the material is defined as the amount of heat required to raise the temperature of 1 mole (the mass in grams of the substance’s molecular weight) 1º C.

Energy can also flow out of a system if the environment is colder than the coffee. The behavior of heat when two systems (the environment and green coffee) are interacting is dictated by the second law of thermodynamics: heat will always flow from the hot system to the cold system. This tendency towards equilibrium is referred to as “entropy”\(^9\).

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\(^6\) Ibid, p. 657

\(^7\) Except where noted, all information in this section is taken from *Water Activity in Foods: Fundamentals and Applications*, edited by Barbosa-Canovas, Fontana, Schmidt, and Labuza. 2007: Blackwell Publishing and the Institute of Food Technology Press, Ames, Iowa


The escaping tendency of a substance is referred to as its “fugacity” and with water it can be measured directly above the substance. This fugacity is a measure of pressure, how hard the water is pushing out of the system. Since water activity was designed to measure change, the measurement is a ratio between the measured vapor pressure current state of the substance and a known standard state; for water activity the standard is pure liquid water at the same temperature at 1 atmosphere of pressure. A typical water activity measurement would be “0.60 @ 25º C”, indicating that the ratio of water pressure above the substance to that of pure water is 0.60 (at the same temperature of 25º C).

The measurement of water activity is dependent upon the temperature of what is being measured. One of the main reasons for measuring $A_w$ is because different substances have different properties of water retention or evaporation than pure water. As a result, if the temperature of the substance being measured is lower, the vapor pressure of the substance will often be higher than the vapor pressure of water at the same temperature, resulting in a higher moisture activity measurement at a higher temperature.

The relationship of $A_w$ to MC (total moisture content) is referred to as the sorption isotherm, graphically illustrated in Figure 1. Experimental results with a variety of foods show that different regions of the sorption isotherm create conditions conducive to certain types of damage. The graph in Figure 1 generally applies to most substances; however, each food has its own characteristic isotherm.

Figure 2 shows the diagram from Sivetz and Desrosier plotting relative humidity of the coffee against total moisture.
Figure 1: Water activity stability diagram showing regions of the graph and potential damage at different levels of Aw.

Figure 2: Humidity vs. moisture content from Sivetz and Desrosier (Coffee Technology, p. 176).

The measurement refers to the equilibrium pressure at the present state, but this state changes over time, especially if a substance is taking on water or drying out. The
isotherm is often used to determine a critical gain or loss of moisture and equations have been developed for the interaction of packaging and food to predict shelf life\textsuperscript{10}. To develop necessary information to make these predictions, several measurements must be taken over time.

Green coffee is considered to be an intermediate moisture substance (this classification includes $A_w$ ranges of 0.60-0.90 and 10%-50% of moisture by weight). In this classification, the main problems (as seen in Figure 1) are likely to be lipid oxidation, non-enzymatic browning reactions, enzymatic actions, and (at the upper level) mold.

\textit{Difference between water activity and total moisture}: A question often arises as to the difference between measuring water activity and total moisture. One way to think about it is in terms of the difference between matter and energy. Matter is something substantial and has mass, while energy has a tendency to dissipate and otherwise seek to come to equilibrium, often making changes to matter as it seeks equilibrium, such as changing the temperature of something or initiating chemical processes.

The total moisture indicates the amount of matter that is present in the form of water (and is measured as a percentage of the mass by weight), while water activity indicates what the water is doing and how active it is (and is measured in thermodynamic terms). As has been seen, under many conditions green coffee is hygroscopic and will take on moisture. This moisture is at the surface and will be indicated by a higher than normal water activity reading (as high as 0.78@20$^\circ$C will tend to cause mold).

High water activity can also indicate microbial activity; this author has found that “sour” beans have considerably higher water activity.

\textbf{Chemical Mechanisms and Types of Post-Processing Damage}

Though green coffee is not necessarily viable (capable of germination) at the 10-12% moisture content at which it is shipped, it retains many of the characteristics of a living seed. One of the main processes that take place in the green beans is the process of respiration, in which oxygen from the environment and carbohydrates and proteins within the bean are consumed by enzymatic activity to create CO$_2$ (carbon dioxide) and H$_2$O (water).

\textit{Respiration}: The process requires moisture, oxygen, and temperature to take place and is an exothermic reaction that itself generates heat. For example, respiration of 100 gm of grain results in 4.4 mg CO$_2$ and a raise in temperature of 0.25$^\circ$C\textsuperscript{11}. During periods of potential respiration, it is important to maintain air circulation and minimal storage temperatures. If the coffee is allowed to take on too much moisture, the effect is cyclic,

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with the higher moisture and temperature produced by respiration maintaining respiration conditions and causing further damage\textsuperscript{12}.

\textbf{Oxidation-reduction reactions:} Redox (reduction-oxidation reactions) of chlorogenic acids (CQA), important flavor precursors in the green bean, can occur under both aerobic (with oxygen present) and anaerobic (without oxygen present) conditions. These reactions are also cyclic; once a quinone is created through oxidation of CQA, they are capable of generating further oxidation without the presence of oxygen. These processes occur to a greater extent in unripe beans\textsuperscript{13}. It should be kept in mind that in this discussion “oxidation” refers to the chemical process of losing electrons, not necessarily anything to do with the atom or compound oxygen (though oxygen is often involved with the reaction), while the “reduction” process refers to gaining electrons.

The “woody” taste noted in coffee that has deteriorated was positively correlated to the production of glucose as a result of the hydrolysis of sucrose\textsuperscript{14}. During hydrolysis, the disaccharide sucrose is broken into its components of fructose and glucose, called “reducing sugars” due to their tendency to react with other components.

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{sucrose_hydrolysis.png}
\caption{Hydrolysis of sucrose. When heated to above 40 degrees C, the water molecules on the outer edge of the sucrose molecule exert a force that causes the bonds in the sucrose to break, releasing heat and changing 1 atom of sucrose to 1 of fructose and 1 of glucose.}
\end{figure}

\begin{flushleft}
\textsuperscript{12} Rojas, “Green Coffee Storage”, p. 734
\textsuperscript{13} Montavon, et al (Nestle’s Research Center), Evolution of Green Coffee Protein Profiles with Maturation and Relationship to Coffee Quality, http://www.aseanfood.info/Article/11015780.pdf
\end{flushleft}
**Lipid components:** In addition to the moisture examined in the previous section, the lipid components (waxes and oils) of green coffee are important in the storage of coffee and changes in their chemical composition reflect changes in quality, though the reasons for these changes are not completely understood in all cases. Arabica coffees have an average of 15% lipids, while Robustas contain 10% or less. Most oils are located in the endosperm (center) of the bean, though a small amount of coffee wax (0.2-0.3% of the bean weight) is located on the outside of the bean. A correlation between coffee quality and both coffee wax and phenolic redistribution within the bean has been observed, with the compounds being more homogeneously distributed throughout the bean as the coffee ages\textsuperscript{15}.

The oils are composed mainly of the common edible vegetable oils found in most plants, along with the coffee wax mentioned in the previous paragraph. The content of fatty acids at the time of coffee harvest is low, but these increase upon storage. Storage at higher humidity and temperature accelerates the rate of increase of the fatty acid fraction of the lipids, though atmospheric composition (availability of oxygen) appears to have little effect. Deterioration at a storage temperature of 40º C, especially coffee that was artificially moistened to a level of 13.5%, was particularly noted. The increase in fatty acids was correlated to degradation of sensory quality of brewed coffee, though the exact parameters of this evaluation were not given in the study\textsuperscript{16}.

**Enzymatic activity:** The blue green color of coffee is due to two types of enzymes: peroxidase and polyphenol oxidase. These gradually decrease as the coffee ages over time of storage. Coffee deterioration appears to start in the coffee membrane as the result of polyphenol oxidase activity. While it is this enzyme that is partially responsible for the desirable blue-green color, increased relative humidity and air temperature affect the membrane (coffee cell wall) structure and permeability, releasing this enzyme (along with peroxidases, compounds having an oxidative effect).

An increase in these was noted when the bean was subjected to higher temperatures and humidity, followed by low enzymatic activity, leading to higher fatty acids and potassium leaching, both of which are characteristic of low-grade coffee. At a microscopic level, the oxygen catalyzed by this activity can be observed as bubbles in the outer layer of the green bean\textsuperscript{17}.

**Phases of Processing and Storage**

**Drying and Hulling:** Initially, when wet processed green coffee comes out of the fermenting tank, it is important to remove excess moisture as quickly as possible, especially the moisture that is lodged in between the parchment and green bean. After

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\textsuperscript{17} Amorim et al, “Biochemical, Physical, and Organoleptical Changes During Raw Coffee Quality Deterioration”.

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this initial stage, if coffee is dried too quickly, two phenomena have been noted: (1) the
outside of the bean shrinks and makes it difficult for moisture to move within the grain and/or (2) too much heat is absorbed and the protective parchment is cracked. Careful
temperature control is also necessary to prevent damage since as the coffee dries it tends
to gain heat more rapidly. This can lead to observable fading of color (referred to as
“bleaching” in some literature).

As noted previously, measurements of green coffee moisture are an average of the
different moistures in beans of different physical properties. The best way to avoid a wide
range of moisture contents is through “slow drying” so the moisture of different sized
beans will evaporate more uniformly and beans can exchange moisture. It is still
possible that though coffee is dried at a proper temperature, some beans may retain
moisture content higher than 12%, resulting in “wet spots”. These tend to bleach over
time and can also cause “cardenillo”, a defect caused by micro-organisms that leave a
yellowish-reddish dust.

Storage in parchment: In growing countries, storage in parchment has long been known
to preserve flavor over time and it is assumed that this is due to reducing the ambient
influences of moisture, oxygen, and temperature. The respiration process is general to all
seeds. Coffee is unique in one aspect, however; due to the presence of parchment, an air
layer forms between the actual green coffee and the parchment itself, resulting in change
of heat and mass transfer, shrinkage, and diffusivity. While the green bean itself is
hygroscopic, the parchment, which is composed of 24.40% lignin (high molecular weight
woody fiber), 66.65% complex carbohydrates (such as cellulose), and 8.95% other fiber
is not, which makes it a barrier to excessive moisture getting to the green beans.

Length of storage in parchment also affects the seed viability (“viability” refers to the
ability of the coffee seed to germinate and become a plant). It has been observed in
several studies that loss of viability over time correlates with loss of coffee flavor due
to change in metabolic reactions or to other chemical processes. Coffee in parchment
retains its viability for a longer period of time than green coffee; in its green form, about
50% of coffee lost its viability within the first 3 months, but in parchment 50% were still
viable after a year in storage.

18 Sivetz and Desrovier, Coffee Technology, p. 171.
21 Sivetz and Desrosier, Coffee Technology, p. 172.
24 Sivetz et al, Coffee Technology, pg. 174
25 Correa et al, “Hygroscopic equilibrium and physical properties evaluation affected by parchment
694-702
After loss of viability, the polyphenol oxidase enzyme responsible for forming a blue-green color in green coffee becomes inactive within a short period, leading to the possibility of color analysis as an indicator of length of storage\textsuperscript{28}. An easy test for viability (which should correlate to coffee quality) is to germinate a randomly selected sample of seeds and counting how many germinate\textsuperscript{29}. Coffee can remain viable for 5 months if it has a total moisture content of 15-18% humidity and is stored in conditions of 5-15º C and a relative humidity of 35-55%\textsuperscript{30}, but these conditions are unlikely for green coffee storage and transport.

**Coffee storage and transport:** When the green coffee is shipped, it is subject to a less controlled environment. The initial state and packaging of the coffee will govern the stability of the coffee as it meets different conditions of temperature and humidity. If the coffee is in a state of respiration, it requires a period of “reposo” or rest in cool ventilated conditions to reduce the rate of respiration.

One of the main problems noted in several studies is the variation of temperature and its effect. Equilibrium moisture content increases as temperature decreases (negative correlation) and both total moisture and water activity of green coffee increase\textsuperscript{31} as the result of condensation. In maintaining the low temperatures necessary to reduce coffee metabolism, both the environmental temperature and the intrinsic temperature of the coffee must be taken into account\textsuperscript{32}.

If the temperatures are alternated between hot and cold, condensation of moisture on the outside of the bean can result. The bean should not be exposed to a relative humidity of greater than 60% and at 75% mold formation becomes a potential problem\textsuperscript{33}.

Temperature fluctuation is found to increase the relative humidity within the storage space\textsuperscript{34}. In controlled tests using green coffee with 11% moisture (A\textsubscript{w} not given), the coffee was tested at relative humidities of 80, 87, and 95% at a temperature of 25º C. A second test was conducted with alternated temperatures of 14 º and 25 º C every 12 hours. (Reminder: other studies show that ideal coffee storage is humidities are at 60-65% at a temperature of 20º C.) Condensation was not observed on the samples held at constant temperature, but it was observed at alternated temperatures.


\textsuperscript{29} Rojas, “Green Coffee Storage”, p. 736.

\textsuperscript{30} Ibid


\textsuperscript{33} Rojas, *Green Coffee Storage*, p. 737.

Moisture gain was steady (linear) at the constant temperature for all three humidities, though there was significant moisture gain in all cases with greater rates of moisture absorption at the higher humidities. After 15 days of storage, there was a significant difference between samples maintained at the constant temperature and the alternated temperatures, with the alternated temperature showing greater moisture gain. The results from the study are illustrated in Figure 4.

![Figure 4: Illustration of data from Palacios-Cabrera et al. "Constant" refers to the tests done at a constant controlled temperature of 25º C and "alternating" refers to the tests where the temperature was alternated between 14º and 25º C every 12 hours.](image)

Blanc and Gumy of Nestle’s undertook a series of experiments recording the temperature and relative humidity using data loggers for green coffee as it was transported. They identified periods of most likely risk, including storage of the container in a north European harbor at low temperatures and transport of green coffee in producing countries. Their tests found that there was little damage or variation of conditions during the maritime transport phase unless the container was stored above-board and high temperatures were encountered. In the latter case, green coffee at the top of the container was most affected. Cardboard liners were utilized in the test containers^{35}.

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A list of recommendations for warehouses of coffee (from the Rojas article on coffee storage in Coffee: Growing, Processing, Sustainable Production, edited by Jean Nicolas Wintgens, 2004: Wiley-VCH, Weinheim, Germany) can be seen in Appendix I.

**Evaluation of damaged coffee:** The purpose of evaluating damaged coffee is to determine (1) the type of damage, (2) the extent of the damage, and (3) the source of the damage. The evaluation of the coffee must take into account, obvious mold damage, insect damage, color, and cup quality. Moldy beans develop different colors depending on the mold from black mildew to white, grey, or greenish colors. Insect damage is usually of the type illustrated on most coffee defect posters. Coffee damaged in storage or shipment can be bleached, indicating exposure to high levels of moisture and/or temperature, especially when the beans have been stored for a long period of time\(^{36}\) or rewetted\(^{37}\).

Sensory aspects that relate most closely to coffee deterioration are shown in Table 1.

<table>
<thead>
<tr>
<th>Sensory description</th>
<th>Effect on green coffee</th>
<th>Potential causes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baggy</td>
<td>Absorbs aromatics from being in direct contact with bag (distinct from “old crop”, discussed below)</td>
<td>Lengthy storage, storage of shorter times at high moisture content, re-using bags, treating bags with hydrocarbon oils</td>
</tr>
<tr>
<td>Moldy</td>
<td>Fungus develops</td>
<td>Improper drying, storage of wet coffee under conditions of poor ventilation, condensation during transport or storage due to alternating temperature and/or high humidity</td>
</tr>
<tr>
<td>Earthy</td>
<td>The green coffee absorbs microbes originating from soil</td>
<td>Combination of drying, handling, and storage: coffee comes into direct contact with dust or earth to become contaminated, especially under half-dry storage conditions; the problem gets worse under high humidity and temperature conditions.</td>
</tr>
<tr>
<td>Onion</td>
<td>Propionic acid develops</td>
<td>Storage under humid conditions</td>
</tr>
<tr>
<td>Old or past crop</td>
<td>Degeneration of beans</td>
<td>Normal over time, but accelerated under conditions of high heat and</td>
</tr>
</tbody>
</table>

\(^{36}\) Ibid, p. 743.

humidity; can also occur more quickly stored in dry climates (humidity of less than 40%).

| Contamination | Coffee absorbs aromatics | Coming into contact with other products such as sulfur, cardamom, oils, soaps, etc. that have volatile components. |

**Potential coffee storage solutions:** Coffee is usually stored in bags that are porous enough to allow air movement; this is to allow the coffee to remain at equilibrium. Allowing free passage of air also reduces the buildup of heat as the result of green bean respiration. However if the beans come into contact with high humidity, the beans may pick up moisture; if they are subject to high humidity (or changes in temperature and humidity), they are likely to suffer deterioration.

Storage in closed sealed bags would reduce the moisture exchange with the environment. However, one must ensure that the coffee is in a “steady state” before packaging. This includes storage conditions; even if the coffee has been properly dried, if stored under fluctuating humidity and temperature conditions, the coffee may be enter a state of respiration and not be ready to package. In any case, sealed green coffee should be protected from fluctuations of temperature as this can cause most of the moisture problems noted to occur.

In this review, no justifications for vacuum packaging were found. While the content of O₂ influences the metabolic rate by accelerating respiration, the amount reduced by vacuum packaging is not enough to affect the rate of respiration due to the porosity of the green beans. It is possible that if the bag were flushed with nitrogen or CO₂ that the respiration process could be slowed, but some oxygen has been absorbed and peroxidases have formed prior to packaging that can cause deterioration under adverse conditions.

**Summary:** There are a number of pathways to coffee deterioration of quality, but they appear to have in common the fact that deterioration is accelerated if the coffee is subjected to high moisture and temperature. The main pathway of deterioration is respiration, which causes changes in the internal chemistry, having specific effects on oils, enzymatic activity, and carbohydrates. Deterioration begins at the surface of the bean (described in several studies as white, bleached, or with similar language).

Potential problems begin with the drying stage of processing. Drying too quickly in the beginning stages can lead to broken parchment, which subjects the inner beans to changes in humidity and temperature. Uneven drying (or drying too quickly throughout the process) leads to “wet spots” leading to deterioration and bleaching.

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38 Sivetz and Desrosier, Coffee Technology, p. 313.
Storage and transport problems can also occur. Green coffee is at its most stable while stored in parchment at a humidity of 60% and a temperature of 20º C, but can still absorb moisture when subjected to extremes of moisture and temperature. The greater the variations of temperature during transport, the faster the deterioration; these conditions were most notable in transport within growing countries and while stored at extremes of hot or cold in importing countries.

Possible measurements to determine the state of the coffee include total moisture, water activity, color, and percent of seed viability. Total moisture indicates if the coffee is at an adequate state to ship, while water activity should indicate thermodynamic activity, degree of respiration, and other potential problems, such as possible condensation of moisture at the surface of the bean. If a bean has the desired moisture content but higher water activity, care should be taken not to expose it to extreme conditions of moisture or temperature and it should not be placed in a sealed package.

Possible problems:

- The coffee is initially dried too quickly and its viability reduced, resulting in high respiration, greater absorption of oxygen, and premature aging.
- The coffee reaches a temperature of higher than 45º C during the early stages of drying, causing a rupture of the parchment, possible degradation of sugars through hydrolysis, and premature bleaching if exposed to high humidities and/or temperatures.
- The green coffee is removed from parchment and allowed to rest under conditions of high humidity and/or temperature. This would increase the moisture content and associated respiration of the green bean.
- The coffee is stored under conditions of low ventilation. This makes it more likely that the moisture present in the bean either through respiration or ambient humidity will be absorbed or condensed on the surface.
- The green coffee is packed in a closed system at too high of a moisture content or water activity. As has been seen, green coffee is capable of gaining moisture under certain conditions and the respiration process must have reached a low level prior to packaging.
- Extreme changes of temperature and humidity during the various stages of transport and storage.
Appendix I: Recommendations for Green Coffee Storage Warehouses


1. Good air ventilation, either by design or orientation of the facility or by use of mechanical equipment such as fans.
2. Prevention of entry of birds, rodents, and insects by physical means such as use of screens.
3. Level ground to ensure safe handling. The floor itself should be cleanable and not absorb moisture to a great degree. Coffee should always be stored on pallets above the floor to allow proper air circulation.
4. Heat traps installed on roof to minimize high temperatures.
5. Permanent regular cleaning and maintenance.