



# Thermophysical properties of fruit—a review with reference to postharvest handling

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## Abstract

The thermophysical data of fruit is vital to the study and optimization of postharvest handling processes. However, data available in the literature are not always consistent and must not be used directly. It is crucial to examine the accuracy and reliability of the property data. Also, models to predict the thermal properties of fruit are not distinctly identified and included in the list of models for food materials. The aim of this review is to show the gaps in fruit properties data with emphasis on those properties that are important during postharvest handling. This paper also presents a review of the measurement and prediction techniques for the thermophysical properties of fruit. Fruit thermophysical properties vary with temperature, moisture content, cultivar, and even between the various parts of the same product. The presented review is a valuable input for developing mathematical models that predict cooling rate, cooling time, cooling uniformity and refrigeration energy usage during postharvest handling processes (e.g. precooling and cold storage), as well as for applications related to prediction and monitoring of temperature induced fruit quality changes.

**Keywords** Cold chain · Refrigeration · Processing · Thermal conductivity models · Specific heat capacity · Thermal diffusivity · Postharvest technology

## Introduction

Fruits are seasonal and have limited shelf life before senescence and associated losses. A common postharvest challenge is to prolong the shelf life of perishable commodities for the fresh market. This is achieved through strict control of environmental conditions (airflow, temperature, humidity) and gas composition in the atmosphere during postharvest handling. This includes rapid cooling of the produce immediately after harvest and control of temperature and humidity during storage, transportation and at the retail display [1, 2]. Cooling of produce reduces the respiration, enzymatic

activities, the growth and proliferation of microorganisms, thus retarding deterioration. The control strategies are governed by the thermophysical properties of the produce, the ambient condition and the associated packaging and handling accessories [3–6]. Understanding the rate and degree of heat and moisture exchange between the produce and its surroundings is crucial to achieve the desired quality, shelf life and market price.

The cold chain processes during postharvest handling involve creating chilled air at the optimum storage temperature using a refrigeration system and maintaining uniform circulation of the chilled air through and around the stack of produce by using air circulation units. The sizing, selection and operation of the refrigeration and air circulation systems requires knowledge of the thermophysical properties of the produce, the packaging, temperature and humidity of the surrounding air [3–5, 7–9]. Mathematical models are frequently used to study the cooling rate, cooling uniformity and energy usages of precooling, cold storage and refrigerated transport of produce. The reliability of these models are dependent on the accuracy of the thermophysical data [9–19].

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The main thermophysical properties relevant for modelling and analysis of thermal postharvest processes are thermal conductivity ( $k$ ), thermal diffusivity ( $\alpha$ ) and specific heat capacity ( $C_p$ ) of the cooling medium (which is usually air), the produce and the packaging material. These values are interrelated as  $C_p = k/\rho\alpha$ , where  $\rho$  is the density of the material. Thermal properties of materials involve parameters associated with the three modes of heat transfer: radiation, conduction, and convection. Radiation is the transfer of heat through electromagnetic waves. This form of heat transfer is crucial before harvest when fruit is hanging on the tree. Radiant waves from direct sunlight during the summer months can result in sunburn damage and losses due to sunburn damage is a major source of economic loss in the marketing fresh fruit due to fruit discolouration and variability in texture [20]. Conduction is the movement of heat to or from the produce due to temperature gradient. In fruit, like all materials, conduction of heat is dependent on the produce thermal conductivity which is also affected by factors like the fruit moisture content and porosity [3, 21]. Convection involves the combined processes of conduction (heat diffusion) and advection (heat transfer by bulk fluid flow). In postharvest handling of produce, the bulk fluid is usually chilling air from the refrigeration unit. In hydro cooling cases, it is chilled water. The chilling air is forced to flow through and around the stacked produce to extract the excess heat from the produce and circulate back to the refrigeration unit to reject the extracted heat [22, 23].

Thermal operations in the postharvest deals with living materials characterised by properties with strong spatial and temporal variability [24]. During processing, the thermal properties of these materials change in time and space depending on the composition, the physical structure of the food and the ambient condition [25–27]. For instance, for stone fruit like plums, there could be significant property differences between the seed and the flesh parts of the fruit. It is important to know the cooling history of the flesh part, the stone part and the stone-flesh interface to accurately model the heat transfer phenomena. If the seed part is prominent, it plays a significant role in the moisture and heat transfer process [28]. Hence, the error incorporated in models that uses a single average or effective property value could be significant [29].

In this paper, a review of the thermophysical properties of fruit relevant to postharvest handling are presented and discussed, including an overview of the thermal treatments applied to maintain quality. In addition, recent advances in the measurement and prediction of fruit thermophysical properties are highlighted.

## Thermal treatments for postharvest handling of fruit

Thermal processing involves transfer of heat energy to or from a product. Table 1 summarizes some of the most common thermal treatment processes during postharvest handling of fruit. Precooling is the quick removal of the field heat shortly after the harvest of a crop. Different methods of precooling are available, including room cooling, forced-air cooling, vacuum cooling, hydro cooling or spray cooling and package icing. Among these, forced-air cooling (FAC) is the most favoured cooling technique [12, 30]. Fruit for distant markets should be kept cool and at the optimum condition during transportation. Refrigerated containers (reefers) are the most used means of transporting fresh produce to distant markets. Reefers are designed to distribute chilled air from the floor, via specific T-shaped decking. The air delivery system should be powerful enough to ensure enough and uniform flow of air through the stacked produce inside the shipment [31, 32].

Refrigerated storage room is used to keep the quality of produce beyond their normal shelf life. Chilled air is constantly circulated through the stack by use of air driving equipment and heat is removed from the produce and other sources by the refrigeration/cooling unit. In addition, cold storage rooms are occasionally used for additional treatments like gassing and fungicide applications [33, 34]. As in the precooling process, the effectiveness of the air distribution, heat exchange and energy usage of the storage operation are affected by the design of packaging boxes and their stacking patterns in the room. Non-uniform flow of air inside the cool store could cause uneven cooling leading to loss of product quality.

Retail (display) cooling systems minimizes radiation and other sources of heat during sales in stores and supermarkets. While keeping the produce cool, display coolers should allow good visibility and ensure free access to stored food for shop customers. This is accomplished by an insulation barrier called air-curtain developed by recirculating air from the top to the bottom of the display structure. The air curtain is a non-physical barrier between chilly air inside the case and the warm shop environment. The modelling and thermal analysis of the air curtains is required to assess the effect of air circulation in front of the cabinet and the disturbance created by the consumers taking food from the shelves [35–37].

## Modelling the thermal processes in the postharvest

The modelling of the thermal processes in the postharvest is based on the mathematical statement of the conservation

**Table 1** Thermal treatments in postharvest handling of fruit

| Thermal treatment | Examples                    | Mode of action                                                                                                                                                                                                                           | Reference(s)       |
|-------------------|-----------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------|
| Cold treatment    | Precooling                  | Fruit temperature is brought down to the recommended storage temperature in the shortest time possible to reduce detrimental fruit physiological and biological changes. Methods used include hydro cooling, forced air cooling etc      | [16, 23, 99]       |
|                   | Refrigerated transport      | Fruit are transported in reefers that are maintained at recommended temperature and relative humidity of particular fruit. Aim is to minimise detrimental physiological and biological changes in fresh fruit                            | [31, 32, 100, 101] |
|                   | Refrigerated storage        | Fruit are kept in a room maintained at the recommended temperature and relative humidity for a particular fruit. Aim is to minimise detrimental physiological and biological changes in fresh fruit                                      | [34, 40, 102, 103] |
|                   | Refrigerated retail display | Fruit are displayed in cabinets on shelves maintained at the recommended temperature and relative humidity conditions. Aim is to minimise detrimental physiological and biological changes in fresh fruit                                | [36, 37, 104–106]  |
| Heat treatment    | Hot air treatment           | Hot air between 35 and 39 °C is blown onto the fruit. Helps control insects, prevent fungal development, reduces chilling injury in citrus, increases sugar levels, decrease polyphenol oxidase action, increase in stress proteins, etc | [107–110]          |
|                   | Hot water treatment         | Fruit is dipped in water at varying temperatures for varying times up to 63 °C for less than one minute. This may trigger increase in sugars and fatty acids, increase flavonoids, induce defence cell and structure proteins, etc       | [109–112]          |
|                   | Intermittent warming        | Intermittent warming is the periodic exposure of fruit under cold storage to short warming cycles. Reduces fungal proliferation and chilling injury in some fruit                                                                        | [110, 113, 114]    |

laws (conservation of mass, momentum and energy). The continuity Eq. (1) and Reynolds-averaged Navier–Stokes (RANS) Eq. (2) are the basic mathematical formulations that govern the motion of the cooling fluid.

$$\nabla \cdot \mathbf{U} = 0 \quad (1)$$

$$\frac{\partial \mathbf{U}}{\partial t} + \nabla \cdot (\mathbf{U} \otimes \mathbf{U}) - \nabla \cdot \left( \left( \frac{\mu + \mu_t}{\rho_a} \right) \nabla \mathbf{U} \right) - S_U + \frac{1}{\rho_a} \nabla p = 0 \quad (2)$$

The spatiotemporal distribution of the air temperature and the produce temperature are estimated using additional Eqs. (3) and (4)

$$(\rho_a C_{pa}) \left( \frac{\partial T_a}{\partial t} + \mathbf{U} \cdot \nabla T_a \right) = \nabla \cdot ((k_a + k_t) \nabla T_a) + h_{pa} (T_p - T_a) \quad (3)$$

$$(\rho_p C_{pp}) \frac{\partial T_p}{\partial t} = \nabla \cdot (k_p \nabla T_p) + h_{pa} (T_a - T_p) + Q_r - Q_v \quad (4)$$

Table 2 summarizes the symbols and thermophysical property data required corresponding to the model Eqs. (1), (2), (3) and (4).

Due to the complexity and size-scale of a fully loaded cold storage room and a reefer container, mathematical

**Table 2** Properties in the Reynolds-averaged Navier–Stokes equations

| Property | Description                          | Unit                             |
|----------|--------------------------------------|----------------------------------|
| $\mu$    | The dynamic viscosity of air         | $\text{kg m}^{-1} \text{s}^{-1}$ |
| $\mu_t$  | Turbulent viscosity of air           | $\text{kg m}^{-1} \text{s}^{-1}$ |
| $C_{pa}$ | Heat capacity of air                 | $\text{J kg}^{-1} \text{K}^{-1}$ |
| $\rho_a$ | Density of air                       | $\text{kg m}^{-3}$               |
| $k_{a0}$ | Thermal conductivity of air          | $\text{W m}^{-1} \text{K}^{-1}$  |
| $C_{pp}$ | Heat capacity of the produce         | $\text{J kg}^{-1} \text{K}^{-1}$ |
| $\rho_p$ | Density of the produce               | $\text{kg m}^{-3}$               |
| $k_p$    | Thermal conductivity of the produce  | $\text{W m}^{-1} \text{K}^{-1}$  |
| $k_t$    | Turbulent thermal conductivity       | $\text{W m}^{-1} \text{K}^{-1}$  |
| $h_{pa}$ | Convective heat transfer coefficient | $\text{W m}^{-2} \text{K}^{-1}$  |
| $T_p$    | Temperature of produce               | K                                |
| $T_a$    | Temperature of air                   | K                                |
| $U$      | Velocity                             | $\text{m s}^{-1}$                |
| $T$      | Time                                 | s                                |
| $P$      | Pressure                             | Pa                               |
| $S_u$    | Momentum source term                 | $\text{m s}^{-2}$                |

modelling of these systems is computationally difficult. To this end, the method of volume averaging is employed. This approach assumes the stack as a porous medium and eliminates the complex geometry of stacked packaging systems

[7, 8]. This considerably simplifies the geometry discretization (meshing) step and the subsequent computation. The porous medium approach is obtained by modifying Eqs. (3) and (4) [15, 16, 38]. Taking averages over an elemental volume of the medium we have, for the solid phase, Eq. (5):

$$(1 - \varphi)(\rho C)_s \frac{\partial T_s}{\partial t} = (1 - \varphi) \nabla \cdot (k_s \nabla T_s) + (1 - \varphi) q_s''' \quad (5)$$

and, for the fluid phase, Eq. (6):

$$\varphi(\rho C_p)_f \frac{\partial T_f}{\partial t} + (\rho C_p)_f v \cdot \nabla T_f = \varphi \nabla \cdot (k_f \nabla T_f) + \varphi q_f''' \quad (6)$$

The subscripts  $s$  and  $f$  refer to the solid and fluid (air in this case) phases, respectively,  $C$  is the specific heat of the solid,  $\varphi$  is the porosity of the stack,  $v$  is the volume of the fluid,  $C_p$  is the specific heat at constant pressure of the fluid,  $k$  is the thermal conductivity, and  $q'''$  ( $\text{W m}^{-3}$ ) is the heat production per unit volume [38]. Hence, additionally, properties like porosity and airflow resistances of the porous domain are incorporated for the purpose of applying the porous medium approach. These two additional properties are the properties of the stack determined by the shape, size and stacking of the produce, the packaging design and orientation [15, 39, 40].

## Thermophysical properties of fruit

The heat exchange between a fruit and its surrounding depends on the thermal properties of the fruit and the surrounding cooling medium. The most important properties to analyse thermal processes are thermal conductivity, thermal diffusivity, specific heat and density of the produce, packaging materials and the cooling medium [5, 9, 41–45]. In addition, the respiration and transpiration properties and the accompanying heat and moisture generations during storage of fruit are crucial to design and optimize thermal processes in the postharvest.

The thermal properties of the cooling medium (air) and most packaging materials are well established and can be effortlessly obtained from literature. On the other hand, produce, being biological materials, have thermal properties that vary in time, temperature and moisture content (Table 3). The absence of any consistent trend is apparent in Table 3. This signifies the caution required when using literature data in prediction models. Also, there may be considerable difference between fruit parts. This is especially important for fruit containing prominent stony-core surrounded by fleshy or pulp tissue, such as mangoes, cherries and plums [28]. The ligneous core—the seed has radically different physical and may thus have thermal parameters different from those of the edible part, the pulp. In a study

on the thermal properties of pomegranate fruit, Mukama et al. [46] found that the aril part of the fruit recorded higher values of specific heat capacity and thermal conductivity compared to the mesocarp and peel, while the peel had the lowest density.

## Specific heat capacity of fruit

The specific heat capacity ( $C_p$ ) of a material determines the amount of heat needed to raise the temperature of one kilogram of mass by 1 K [47]. Specific heat values of whole fruit ranged from 1.72 to 4.05  $\text{kJ kg}^{-1} \text{K}^{-1}$  with an average value of 3.74  $\text{kJ kg}^{-1} \text{K}^{-1}$ . Fruit with high water content generally have higher specific heats. For example, melons have average specific heat capacity of 4.05  $\text{kJ kg}^{-1} \text{K}^{-1}$  [48].

Specific heat values have been reported to increase with an increase in fruit moisture content. A similar trend is reported with regards to temperature [47, 49–52]. The effect of moisture content has however shown to be strong compared to temperature [50, 53]. Kumar et al. [44] reported a linear increase of specific heat of tomatoes with temperature ranging from 30 to 130 °C, just like Aghbashlo et al. [50] for berberis between 50 and 70 °C, (1.97–3.28)  $\text{kJ kg}^{-1} \text{K}^{-1}$ . On the other hand, Singh et al. [54] reported negligible effect of temperature on the specific heat of unfrozen food products. Different cultivars of the same fruit may also have different specific heat values. For instance, at 40 °C, 50% moisture content, Golden Delicious, Idared, Jonagold and Jonathan apple cultivars had specific heat capacity of 3.22  $\text{kJ kg}^{-1} \text{K}^{-1}$ , 3.04  $\text{kJ kg}^{-1} \text{K}^{-1}$ , 2.82  $\text{kJ kg}^{-1} \text{K}^{-1}$ , and 2.42  $\text{kJ kg}^{-1} \text{K}^{-1}$ , respectively [55]. This is linked to difference in fruit material composition and microstructure [41].

## Thermal conductivity of fruit

Thermal conductivity ( $k$ ) measures the heat conducting ability of a material. Materials with low thermal conductivity have a lower rate of heat transfer than materials with high thermal conductivity. Fruit thermal conductivity values ranged between 0.13 and 0.89  $\text{W m}^{-1} \text{K}^{-1}$ , average 0.53  $\text{W m}^{-1} \text{K}^{-1}$  (Table 3). Similar to specific heat capacity, fruit with high moisture content have higher values of thermal conductivity. This is attributed to the higher thermal conductivity of water compared to other fruit contents [41, 56]. From data that had fairly close measurement method and conditions where stated (Table 3), the variation between same fruit values of thermal conductivity, taking the bigger value as the denominator, was 8.81% in pear [57, 58]. Both authors used the probe method. This variation can be attributed to fruit varietal differences (microstructure) and measurement error [41, 42].

**Table 3** Thermal properties of different horticultural fruit from literature

| Category | Fruit type       | Temperature (°C) | Moisture content (%) | Density, $\rho$ (kg m <sup>-3</sup> ) | Thermal diffusivity, $\alpha$ ( $\times 10^{-7}$ m <sup>2</sup> s <sup>-1</sup> ) | Specific heat capacity, $C_p$ (kJ kg <sup>-1</sup> K <sup>-1</sup> ) | Thermal conductivity, $k$ (W m <sup>-1</sup> K <sup>-1</sup> ) | Reference(s) |
|----------|------------------|------------------|----------------------|---------------------------------------|-----------------------------------------------------------------------------------|----------------------------------------------------------------------|----------------------------------------------------------------|--------------|
| Pomes    | Apple            | 30               | —                    | 813                                   | 1.36                                                                              | 3.81                                                                 | 0.42                                                           | [61]         |
|          | Apple            | 40               | —                    | 813                                   | 1.51                                                                              | 3.86                                                                 | 0.48                                                           | [61]         |
|          | Apple            | 50               | —                    | 813                                   | 1.72                                                                              | 3.85                                                                 | 0.54                                                           | [61]         |
|          | Apple            | 40               | 88                   | —                                     | 1.78                                                                              | —                                                                    | 0.54                                                           | [115]        |
|          | Apple            | 6–28             | —                    | —                                     | 0.88–1.19                                                                         | —                                                                    | 0.404–0.423                                                    | [62]         |
|          | Apple            | 0–30             | 85                   | —                                     | 1.37                                                                              | —                                                                    | —                                                              | [116]        |
|          | Apple            | 40               | 88                   | —                                     | —                                                                                 | 3.83                                                                 | —                                                              | [117]        |
|          | Apple (green)    | 28               | 88.5                 | 790                                   | —                                                                                 | —                                                                    | 0.422                                                          | [57]         |
|          | Apple (red)      | 28               | 84.9                 | 840                                   | —                                                                                 | —                                                                    | 0.513                                                          | [57]         |
|          | Apple (red)      | 0–30             | 85                   | 840                                   | 1.4                                                                               | —                                                                    | —                                                              | [118]        |
|          | Apple (grated)   | 6–28             | —                    | —                                     | 1.28–1.38                                                                         | —                                                                    | 0.553–0.575                                                    | [62]         |
|          | Apple (juice)    | 6–28             | —                    | —                                     | 1.43–1.47                                                                         | —                                                                    | 0.660–0.642                                                    | [62]         |
|          | Pear             | 28               | 86.8                 | 1000                                  | —                                                                                 | —                                                                    | 0.595                                                          | [57]         |
|          | Pear             | —                | —                    | 990                                   | —                                                                                 | —                                                                    | 0.543                                                          | [58]         |
|          | Pear (bartlet)   | —                | 83.8                 | —                                     | —                                                                                 | 3.73                                                                 | —                                                              | [43]         |
| Berries  | Strawberry       | 28               | 88.8                 | 900                                   | —                                                                                 | —                                                                    | 0.462                                                          | [57]         |
|          | Strawberry       | 5                | 92                   | —                                     | 1.27                                                                              | —                                                                    | —                                                              | [116]        |
|          | Straw berry jam  | 20               | 41                   | —                                     | 1.2                                                                               | —                                                                    | —                                                              | [120]        |
|          | Figs             | 23               | 40                   | 1241                                  | 0.96                                                                              | —                                                                    | 0.310                                                          | [120]        |
|          | Avocado          | 41               | —                    | —                                     | 1.54                                                                              | —                                                                    | —                                                              | [116]        |
|          | Avocado          | 28               | 64.7                 | 1060                                  | —                                                                                 | —                                                                    | 0.429                                                          | [57]         |
|          | Avocado          | —                | 74.27                | —                                     | —                                                                                 | 3.67                                                                 | —                                                              | [75]         |
|          | Acerola (pulp)   | 40               | 92                   | 1000                                  | 1.528                                                                             | 4.172                                                                | 0.65                                                           | [51]         |
|          | Tomato (pulp)    | 20–150           | —                    | —                                     | —                                                                                 | 2.25–3.00                                                            | —                                                              | [119]        |
|          | Tomato (pulp)    | 22               | —                    | 1032                                  | —                                                                                 | —                                                                    | —                                                              | [44]         |
|          | Blueberry (pulp) | 40               | 82                   | 1001                                  | 1.51                                                                              | 4.050                                                                | 0.64                                                           | [51]         |
|          | Blueberry        | 84.61            | —                    | —                                     | —                                                                                 | 3.83                                                                 | —                                                              | [75]         |
|          | Blackberry       | 85.64            | —                    | —                                     | —                                                                                 | 3.91                                                                 | —                                                              | [75]         |
|          | Acai (pulp)      | —                | 93.8                 | 1047                                  | —                                                                                 | —                                                                    | —                                                              | [29]         |
|          | Kiwi             | 30–90            | —                    | —                                     | —                                                                                 | 3.893                                                                | —                                                              | [53]         |
|          | Pomegranates     | 25               | 76.5                 | 986.99                                | 1.69                                                                              | 3.302                                                                | 0.546                                                          | [2]          |
|          | Cranberries      | —                | 83.02                | 670                                   | 1.06                                                                              | 3.509                                                                | 0.248                                                          | [120]        |
|          | Cranberries      | —                | 86.54                | —                                     | —                                                                                 | 3.91                                                                 | —                                                              | [75]         |
|          | Raspberries      | —                | 82.7                 | —                                     | —                                                                                 | 3.73                                                                 | —                                                              | [43]         |
|          | Berberis         | 50–70            | 19.3–74.3            | —                                     | —                                                                                 | 1.965–3.281                                                          | 0.132–0.489                                                    | [50]         |

**Table 3** (continued)

| Category | Fruit type          | Temperature (°C) | Moisture content (%) | Density, $\rho$ (kg m <sup>-3</sup> ) | Thermal diffusivity, $\alpha$ ( $\times 10^{-7}$ m <sup>2</sup> s <sup>-1</sup> ) | Specific heat capacity, $C_p$ (kJ kg <sup>-1</sup> K <sup>-1</sup> ) | Thermal conductivity, $k$ (W m <sup>-1</sup> K <sup>-1</sup> ) | Reference(s) |
|----------|---------------------|------------------|----------------------|---------------------------------------|-----------------------------------------------------------------------------------|----------------------------------------------------------------------|----------------------------------------------------------------|--------------|
| Drupes   | Peach               | 28               | 88.5                 | 930                                   | –                                                                                 | –                                                                    | 0.581                                                          | [57]         |
|          | Peach               | 14               | 90                   | 980                                   | –                                                                                 | 3.892                                                                | 0.54                                                           | [121]        |
|          | Peach               | 27.4             | –                    | –                                     | 1.39                                                                              | –                                                                    | –                                                              | [116]        |
|          | Peach (no stone)    | 25–50            | 85.1                 | –                                     | –                                                                                 | 3.77                                                                 | –                                                              | [43]         |
|          | Peach               | –                | 86                   | –                                     | –                                                                                 | –                                                                    | 0.58                                                           | [122]        |
|          | Plums, blue         | 26               | 88.6                 | 1130                                  | –                                                                                 | –                                                                    | 0.551                                                          | [57]         |
|          | Apricots            | 14               | 90                   | 1000                                  | –                                                                                 | 3.134                                                                | 0.5                                                            | [121]        |
|          | Apricots            | –                | 86.35                | –                                     | –                                                                                 | 3.87                                                                 | –                                                              | [75]         |
|          | Cherry (sour)       | –                | 86.13                | –                                     | –                                                                                 | 3.85                                                                 | –                                                              | [75]         |
|          | Plum (no seed)      | –                | 80.3                 | –                                     | –                                                                                 | 3.65                                                                 | –                                                              | [43]         |
|          | Plum                | –                | 68                   | –                                     | –                                                                                 | –                                                                    | 0.54                                                           | [122]        |
|          | Plum                | –16              | –                    | –                                     | –                                                                                 | –                                                                    | 0.245                                                          | [123]        |
|          | Nectarine           | 8.6              | 82.9                 | 990                                   | –                                                                                 | –                                                                    | 0.585                                                          | [57]         |
|          | Nectarine           | –                | –                    | –                                     | –                                                                                 | 3.5                                                                  | 0.65                                                           | [122]        |
|          | Olive (pulp)        | –                | 75.97                | 1057.6                                | 1.239                                                                             | 3.609                                                                | 0.473                                                          | [28]         |
| Melons   | Watermelon          | –                | 95                   | 1003                                  | 1.48                                                                              | 4.05                                                                 | 0.616                                                          | [48]         |
|          | Cantaloupe Melon    | –                | 89.78                | –                                     | –                                                                                 | 3.93                                                                 | –                                                              | [75]         |
| Citrus   | Yellow melon        | –                | –                    | –                                     | –                                                                                 | 4.03                                                                 | –                                                              | [53]         |
|          | Orange (pulp)       | –                | 82.1–82.7            | 1030–1060                             | 1.5–1.56                                                                          | 4.025–4.068                                                          | 0.63–0.66                                                      | [124]        |
|          | Orange              | –                | –                    | 1010                                  | –                                                                                 | –                                                                    | 0.554                                                          | [58]         |
|          | Orange              | –                | 89.2                 | 1004                                  | 1.45                                                                              | 3.91                                                                 | 0.588                                                          | [48]         |
|          | Orange (peeled)     | 28               | 85.9                 | 1030                                  | –                                                                                 | –                                                                    | 0.580                                                          | [57]         |
|          | Lemon               | 40               | –                    | –                                     | 1.07                                                                              | –                                                                    | –                                                              | [116]        |
|          | Lemon               | –                | 90                   | 1032                                  | 1.46                                                                              | 3.93                                                                 | 0.592                                                          | [48]         |
|          | Lemon (peeled)      | 28               | 91.8                 | 930                                   | –                                                                                 | –                                                                    | 0.525                                                          | [57]         |
|          | Lime (peeled)       | 28               | 89.9                 | 1000                                  | –                                                                                 | –                                                                    | 0.490                                                          | [57]         |
|          | Lime                | –                | 90.7                 | 1003                                  | 1.47                                                                              | 3.94                                                                 | 0.595                                                          | [48]         |
|          | Grapefruit (peeled) | 26               | 90.4                 | 950                                   | –                                                                                 | –                                                                    | 0.549                                                          | [57]         |

**Table 3** (continued)

| Category | Fruit type            | Temperature (°C) | Moisture content (%) | Density, $\rho$ (kg m <sup>-3</sup> ) | Thermal diffusivity, $\alpha$ ( $\times 10^{-7}$ m <sup>2</sup> s <sup>-1</sup> ) | Specific heat capacity, $C_p$ (kJ kg <sup>-1</sup> K <sup>-1</sup> ) | Thermal conductivity, $k$ (W m <sup>-1</sup> K <sup>-1</sup> ) | Reference(s) |
|----------|-----------------------|------------------|----------------------|---------------------------------------|-----------------------------------------------------------------------------------|----------------------------------------------------------------------|----------------------------------------------------------------|--------------|
| Tropical | Pawpaw                | —                | 88                   | 889                                   | 1.69                                                                              | 3.88                                                                 | 0.582                                                          | [48]         |
|          | Mango                 | —                | 84                   | 1068                                  | 1.39                                                                              | 3.78                                                                 | 0.562                                                          | [48]         |
|          | Mango (pulp)          | 20–80            | 52–90                | 991.2–1192                            | 1.39                                                                              | 2.730–4.093                                                          | 0.377–0.623                                                    | [59]         |
|          | Mango                 | –10 to –30       | 60–80                | —                                     | 3.904–6.033                                                                       | 1.721–2.031                                                          | 0.677–1.134                                                    | [49]         |
|          | Mango                 | 60–100           | 60–80                | —                                     | 1.433–2.052                                                                       | 3.655–3.919                                                          | 0.507–0.855                                                    | [49]         |
|          | Guava                 | —                | 81                   | 1071                                  | 1.38                                                                              | 3.7                                                                  | 0.547                                                          | [48]         |
|          | Cupuacu (pulp)        | 25–55            | 89.83                | 1036                                  | 1.46                                                                              | 3.82                                                                 | 0.578                                                          | [29]         |
|          | Banana (puree)        | —                | —                    | 980                                   | —                                                                                 | —                                                                    | 0.475                                                          | [58]         |
|          | Banana                | —                | 74.26                | —                                     | —                                                                                 | 3.56                                                                 | —                                                              | [75]         |
|          | Banana (puree)        | 80               | —                    | 1115                                  | —                                                                                 | 3.642                                                                | 0.595                                                          | [125]        |
|          | Banana                | 27               | 75.7                 | 980                                   | —                                                                                 | —                                                                    | 0.481                                                          | [57]         |
|          | Banana                | —                | 71                   | 964                                   | 1.5                                                                               | 3.45                                                                 | 0.498                                                          | [48]         |
|          | Banana (unripe)       | —                | 71–21                | —                                     | 1.97–1.26                                                                         | 1.8–3.0                                                              | 0.894–0.154                                                    | [52]         |
|          | Papaya                | 20               | —                    | —                                     | —                                                                                 | 3.02                                                                 | —                                                              | [126]        |
|          | Caja (pulp)           | 30–90            | —                    | —                                     | —                                                                                 | 4.037                                                                | —                                                              | [53]         |
|          | Pineapple             | 27               | 84.9                 | 1010                                  | —                                                                                 | —                                                                    | 0.549                                                          | [57]         |
|          | Pineapple             | —                | 85                   | 983                                   | 1.52                                                                              | 3.8                                                                  | 0.567                                                          | [48]         |
|          | Cashew apple (pulp)   | 30–90            | —                    | —                                     | —                                                                                 | 4.027                                                                | —                                                              | [53]         |
|          | Cashew                | —                | 88                   | 930                                   | 1.61                                                                              | 3.88                                                                 | 0.582                                                          | [48]         |
|          | Pitanga (pulp)        | 30–90            | —                    | —                                     | —                                                                                 | 3.967                                                                | —                                                              | [53]         |
|          | Soursop fruit (pulp)  | 30–90            | —                    | —                                     | —                                                                                 | 3.865                                                                | —                                                              | [53]         |
|          | Soursop               | —                | 83                   | —                                     | 1.55                                                                              | 3.75                                                                 | 0.557                                                          | [48]         |
|          | Graviola (pulp)       | 25–55            | 88.96                | 1013                                  | 1.5                                                                               | 3.97                                                                 | 0.603                                                          | [29]         |
|          | Cocoa (pulp)          | 30–90            | —                    | —                                     | —                                                                                 | 3.746                                                                | —                                                              | [53]         |
|          | Passion fruit (Juice) | 0.4–68.8         | 50–80                | 995–1240                              | —                                                                                 | 2.5–4.0                                                              | 0.412–0.635                                                    | [35]         |

Mercali et al. [51], Aghbashlo et al. [50], Bon et al. [59], and Figura and Teixeira [26] found more dependency of thermal conductivity on moisture content than temperature. Sweat [57] also found a strong correlation between thermal conductivity and fruit water content except for fruit considerably less dense than water. In a study to determine the thermal properties of Berberis fruit, using the transient line heat source method, Aghbashlo et al. [50] also observed increase in the thermal conductivity with both moisture content and temperature increase [0.1324–0.4898 W m<sup>-1</sup> K<sup>-1</sup>, between 50–70 °C and 19.3–74.3% moisture content).

At low temperatures (–10 to –30) °C, Laohasongkram et al. [49] observed an increase in the thermal conductivity of mangoes with a decrease in temperature. However, thermal conductivity increased with an increase in moisture content. They also observed that the thermal conductivity values of frozen mangoes were higher than values above freezing temperatures. This can be attributed to the higher thermal conductivity of ice (2.23 W m<sup>-1</sup> K<sup>-1</sup>) in comparison to water (0.604 W m<sup>-1</sup> K<sup>-1</sup>) [60].

## Thermal diffusivity of fruit

Thermal diffusivity ( $\alpha$ ) measures the rate at which heat is conducted through a material. It represents the rate of temperature change during temperature removal or addition to a given volume of food product during processing [47]. Thermal diffusivity relates the heat conducting ability of a material to its heat storability [43]. Thermal diffusivity of fruit range between  $0.88$  and  $2.05 \times 10^{-7} \text{ m}^2 \text{ s}^{-1}$ . (Table 3). However, similar to specific heat and thermal conductivity, any comparison of values should be based on measurements done at similar conditions of temperature and moisture content since thermal diffusivity of fruit has been shown to be affected by temperature and moisture content [49, 61–63].

Temperature, moisture content and their interaction significantly affected the thermal diffusivity of mangoes at both low  $-10$  to  $-30^\circ\text{C}$  and high temperatures  $60$ – $100^\circ\text{C}$ , rising with a rise in temperature and moisture content at high temperature measurements [49]. However, at low temperature, a decrease in thermal diffusivity with an increase in temperature was observed for the mangoes. At constant temperature, the diffusivity increased with increase in moisture content [49]. Martínez-Monzó et al. [61] and Bozikova [62] also reported a linear increase of thermal diffusivity with increase in temperature in apples. Fruit growth stage may also affect the thermal diffusivity of fruit. For example, in Marsh grapefruit, Bennett et al. [64] observed an increase in the effective thermal diffusivity as the fruit ripened, lost peel thickness and became denser.

## Measurement techniques

### Measuring the thermal conductivity of fruit

Thermal conductivity is measured in several ways depending on the type of material and the medium temperature. The two main categories of thermal conductivity measurement techniques are steady-state methods and transient methods. The steady-state technique takes measurements when the temperature of the material reaches complete equilibrium that is when the temperature at each point of the specimen is constant and does not change with time. Figure 1 depicts steady-state conduction of heat through a plane wall. Equation (7) gives the corresponding heat conduction equation, also called the Fourier's law, as the rate of heat flow ( $q$ ) through thickness  $dx$ , in the direction normal to surface area  $A$ , under a steady state temperature difference  $dT = T_1 - T_2$ .

$$q = \frac{k(T_1 - T_2)}{dx} \quad (7)$$

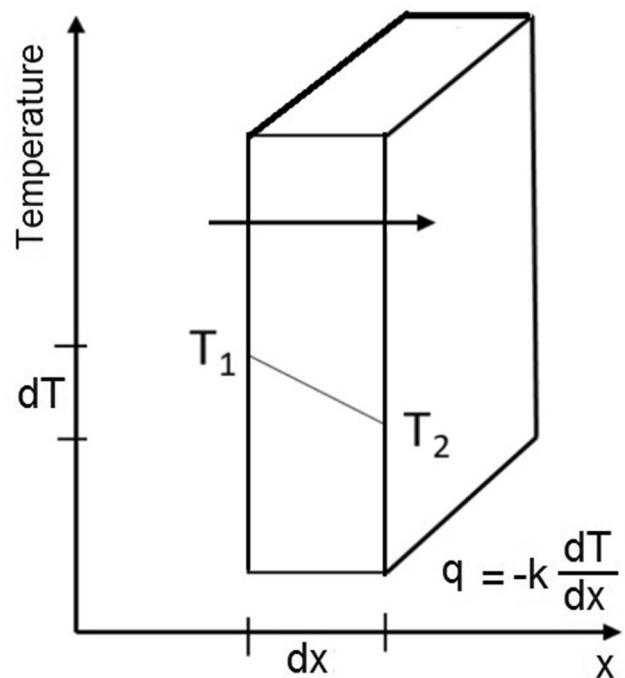


**Fig. 1** Heat conduction through a slab material:  $T_1$  and  $T_2$  are surface temperatures

where  $q$  is the heat flux ( $\text{W m}^{-2}$ ),  $k$  is the thermal conductivity ( $\text{W m}^{-1} \text{ K}^{-1}$ ),  $dx$  is the thickness of the sample (m),  $T_1$  is temperature at the high temperature side and  $T_2$  is the temperature ( $^\circ\text{C}$ ) at the low temperature side of the sample, both kept constant in time. Steady-state technique generally takes a long time to reach the required equilibrium and may be expensive since it requires a well-designed installation system [65]. This technique involves time independent measurements of the thermal conductivity using a heat source and heat sink principle. It is more suited for low moisture products. Notable methods in this category are the guarded hot plate, concentric cylinder and concentric sphere methods. The material to be measured is placed between the plates, one acting as a heat source while the other, a heat sink [66].

The transient or non-steady-state techniques determine thermal conductivity using measurements taken from transient sensors during a heating process. Measurements in this category are relatively quick, which gives it an advantage over steady-state techniques [43]. The disadvantage is that the mathematical analysis of the data is in general more difficult. This technique has been widely used in the determination of the thermal conductivity of most foods and hence it is discussed in greater detail below. Transient methods generally employ needle probes or wires [67] (Fig. 2).

The probe method is based on the solution of the line heat source placed within an infinite, isotropic, and homogenous specimen of thermal diffusivity,  $\alpha$ . Heat flow radially around the probe in the specimen is in accordance

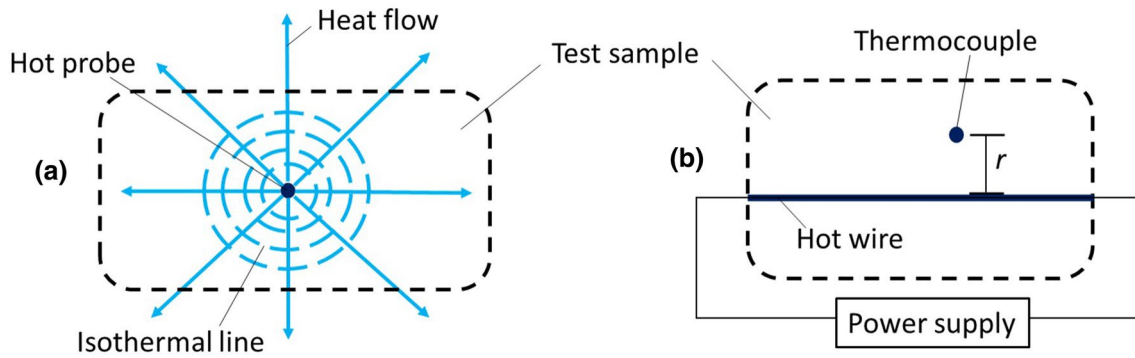


**Fig. 2** Schematic **a** hot needle and **b** hot wire embedded in specimen

to the general Fourier equation. The isotherms formed within the specimen represent perfect cylinders (Fig. 2) of infinite length with continually increasing radii [68]. This is represented by Eq. (8) [65, 69].

$$\frac{\partial T}{\partial t} = \alpha \left( \frac{\partial^2 T}{\partial r^2} + \frac{1}{r} \frac{\partial T}{\partial r} \right) \quad (8)$$

where  $T$  is temperature ( $^{\circ}\text{C}$ ) at time  $t$  (s) and  $r$  is the radial distance from the line source (m). Single and double probes are used in the measurements. Figure 3a depicts schematic view of the single-needle probe technique. In this technique, heat is applied to the needle for a duration of  $t_h$  (s) while simultaneously monitoring the temperature and then the heating is turned-off for an extra duration called the cooling-period. Then models are fitted to the temperature–time data of the heating and cooling periods to provide the thermal conductivity value. For instance, Eqs. (9) and (10) are used to model the temperature–time history of the heating and cooling periods, respectively [69].

$$T = m_o + m_2 t + m_3 \ln t, \quad 0 < t < t_h \quad (9)$$

$$T = m_1 + m_2 t + m_3 \ln \left[ \frac{t}{t - t_h} \right], \quad t > t_h \quad (10)$$

where  $m_o$  is the ambient temperature at time 0  $^{\circ}\text{C}$ ,  $m_1$  is final temperature after heating ( $^{\circ}\text{C}$ ),  $m_2$  is the rate of background temperature drift ( $^{\circ}\text{C s}^{-1}$ ),  $m_3$  is the slope of the line relating the change in temperature against logarithm of time ( $^{\circ}\text{C}$ ) [65]. Once the constants of Eqs. (9) and (10) are determined through curve fitting, the thermal conductivity,  $k$  ( $\text{W m}^{-1} \text{K}^{-1}$ ), is calculated as in Eq. (11),  $q$  is the power dissipated per unit length of heater ( $\text{W m}^{-1}$ ). Data in the linear portions of the graph of the heating and cooling phases are used for fitting the equations as the initial plot of temperature vs  $\ln(t)$  and  $\ln(t/(t - t_h))$  is nonlinear, influenced by probe thermal properties [65, 68].

$$k = \frac{q}{4\pi m_3} \quad (11)$$

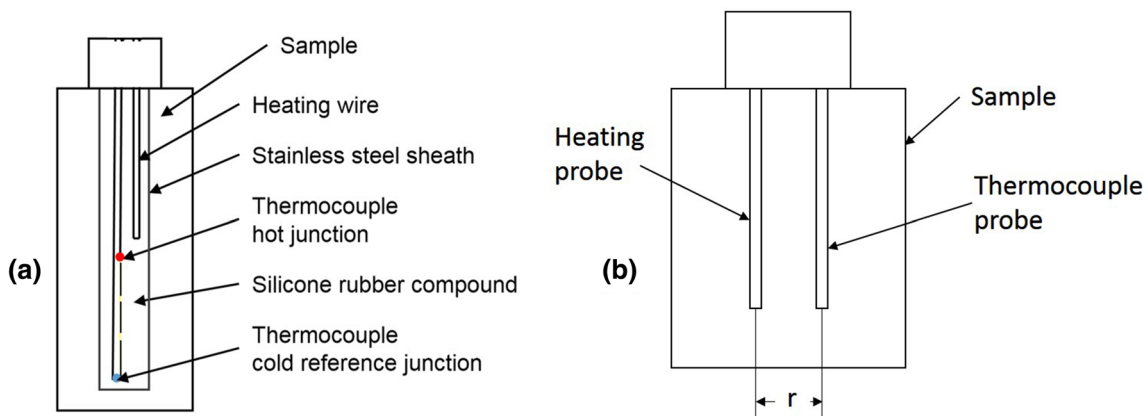


**Fig. 3** Schematic view of the single **(a)** and dual **(b)** needle probes [68]

The dual needle heat-pulse sensor consists two needles spaced typically 6 mm apart (Fig. 3b,  $r=6$  mm). One needle is a line heat source and the other is a thermocouple. A short duration pulse is applied to the heater and the thermocouple's temperature response to the heat pulse is used to determine the thermal properties of the sample. The temperature rise of the thermocouple at distance,  $r$ , is given by Eq. (12) [65, 70].

$$\Delta T = \frac{q}{4\pi kt} \Delta \exp\left(-\frac{r^2}{4\alpha t}\right) \quad (12)$$

where  $\Delta T$  is the temperature rise measured by the thermocouple ( $^{\circ}\text{C s}^{-1}$ ),  $r$  is the distance between the line heat source and the temperature sensor (m),  $q$  is the power dissipated per unit length of heater ( $\text{W m}^{-1}$ ),  $k$  is the thermal conductivity ( $\text{W m}^{-1} \text{K}^{-1}$ ),  $\alpha$  is the thermal diffusivity ( $\text{m}^2 \text{s}^{-1}$ ), and  $t$  is heating time (s). Equation (12) is used to fit a set of observations and with a mathematical inverse method the thermal conductivity and thermal diffusivity are calculated. After obtaining the thermal conductivity, density,  $\rho$  ( $\text{kg m}^{-3}$ ) and thermal diffusivity  $\alpha$  ( $\text{m}^2 \text{s}^{-1}$ ), the specific heat,  $C_p$  ( $\text{J kg}^{-1} \text{K}^{-1}$ ) is calculated from Eq. (13).

$$\alpha = \frac{k}{\rho C_p} \quad (13)$$

Alternatively, the readings can be processed taking into consideration both the heating and cooling phases, Eq. (14) relates to the first  $t$  seconds, while the heat is on and Eq. (15) is for the cooling period, while the heat is off [65, 67]. Hence, the temperature–time data of the heating and cooling periods is fitted to Eqs. (17) and (18) using a non-linear least squares procedure.

$$T = b_0 t + b_1 E_i\left(\frac{b_2}{t}\right) \quad (14)$$

$$T = b_0 t + b_1 \left\{ E_i\left(\frac{b_2}{t}\right) - E_i\left[\frac{b_2}{t - t_h}\right] \right\} \quad (15)$$

$$T = \frac{4\pi(T - T_o)}{q} \quad (16)$$

where  $T_o$  is the ambient temperature at time 0 ( $^{\circ}\text{C}$ ),  $T$  is the temperature after heating time ( $t$ ) ( $^{\circ}\text{C}$ ),  $q$  is the heat input per unit length of probe ( $\text{W m}^{-1}$ ).  $t$  is the instantaneous time when temperature is recorded (s),  $t_h$  is the first seconds (s), while the heat is on,  $b_0$ ,  $b_1$  and  $b_2$  are the constants to be fit. The thermal conductivity,  $k$  ( $\text{W m}^{-1} \text{K}^{-1}$ ) and thermal diffusivity,  $\alpha$  ( $\text{m}^2 \text{s}^{-1}$ ) are then computed using Eqs. (17) and (18),  $r$  is the radial distance between the two needles (m).

$$k = \frac{1}{b_1} \quad (17)$$

$$\alpha = \frac{r^2}{4b_2} \quad (18)$$

## Measurement techniques of specific heat capacity of fruit

Different methods have been used by several researches to determine the specific heat capacity of agricultural and food materials. These include hot wire method (transient line heat source method), method of mixtures, guarded plate method, and differential scanning calorimetry (DSC) [5, 41, 52, 71]. The dual needle probe, described in “[Measuring the thermal conductivity of fruit](#)” above, can be used to determination the specific heat capacity, thermal conductivity, thermal diffusivity, and thermal resistivity of a material.

The method of mixtures is the most widely used technique for measuring the specific heat capacity of agricultural products due to its simplicity [41]. In this method, a sample of interest with a known mass ( $M_{\text{sample}}$ ) is first set at a determined initial temperature ( $T_1$ ) and then added in an adiabatic vessel (a calorimeter) at a determined initial temperature ( $T_2$ ) and with known mass ( $M_{\text{calorimeter}}$ ) and specific heat capacity ( $C_{p(\text{Calorimeter})}$ ). Then, the sample is mixed with a specific mass of a liquid with known properties (water, in general— $M_{\text{water}}$ ,  $C_{p(\text{water})}$ ) at  $T_2$ . After thermal equilibrium the entire system will attain a temperature  $T_3$ , where  $T_2 < T_3 < T_1$ . The sample specific heat capacity ( $C_p$ ) is then obtained by applying the energy balance for the system assuming the heat loss from the sample ( $= M_{\text{sample}} C_p (T_1 - T_3)$ ) is equal to the sum of heat gain by the water ( $= M_{\text{water}} C_{p(\text{water})} (T_3 - T_2)$ ) and the calorimeter ( $= M_{\text{calorimeter}} C_{p(\text{calorimeter})} (T_3 - T_2)$ ) using Eq. (19).

$$C_p = \frac{M_{\text{water}} C_{p(\text{water})} (T_3 - T_2) + M_{\text{calorimeter}} C_{p(\text{calorimeter})} (T_3 - T_2)}{M_{\text{sample}} (T_1 - T_2)} \quad (19)$$

In the DSC method, a single heat thermogram—a record of heat flow as a function of heat or temperature is used to calculate the specific heat of a sample. The thermogram is generated by the system recorder after the sample is placed in a special cell whose temperature is increased at a constant heating rate [47]. The area under the thermogram is proportional to the heat energy absorbed or lost by the product in the heating or cooling process [41]. The DSC method is based on the definition of specific heat rewritten as in Eq. (20) [72, 73]:

$$C_p = \frac{1}{m} \left[ \frac{\partial H}{\partial T} \right] = \frac{1}{m} \left[ \frac{\partial H / \partial t}{\partial T / \partial t} \right] = \frac{1}{m} \frac{\Delta P}{\beta} \quad (20)$$

where  $H$  is the enthalpy (J),  $m$  is the mass (kg),  $T$  the temperature (K),  $\Delta P$  is difference between power to the sample and the reference (W), and  $\beta$  is heating rate (K s<sup>-1</sup>). The DSC method can scan a wide range of temperatures making it suitable for the determination of the effect of temperature on specific heat of foods, however, the equipment is expensive, requires calibration, and uses small sample sizes 5–15 mg [43, 49]. Kumar et al. [44] used the DSC to measure the specific heat of tomatoes at 10 °C intervals between 20 and 130 °C (Table 3).

The guarded plate method of specific heat capacity determination works on the principle that the electric heat supplied to a product in between thermal guards that are also electrically heated in a given time is equal to the heat gain by the specimen (Eq. 21). The specific heat is then calculated from the heat gain as in Eq. (22). The guards and the product are kept at the same temperature [41]. However, this method may not be fit for irregular shaped specimen like fruit unless specially shaped fitting thermal guards are available.

$$Q = C_p W \Delta T = VIt \quad (21)$$

$$C_p = \frac{VIt}{W \Delta T} \quad (22)$$

where  $C_p$  is the specific heat (J kg<sup>-1</sup> K<sup>-1</sup>),  $V$  is the average voltage in time  $t$  (V s<sup>-1</sup>),  $I$  is the average current in time  $t$  (A s<sup>-1</sup>) and  $\Delta T$  is the temperature change (°C). Table 4 presents a summary of some of the common measurement methods for thermal properties and density of fruit.

## Prediction techniques

### Frozen foods: ice fraction

In frozen foods, the fraction of ice strongly affects the thermophysical properties of the food [74, 75]. The thermophysical properties of frozen foods vary dramatically with temperature because the ice and water fractions in the food vary with temperature and these have different thermophysical properties. Initially some water crystallises in the food, concentrating the remaining solution which further lowers its freezing point. Therefore, in predicting the thermal properties of frozen foods, it is paramount to determine how much of the water is frozen and how much remains unfrozen at a given temperature. For example, when determining the thermal conductivity of frozen foods, the thermal conductivity of the ice/water mix is determined and then combined successively with the thermal conductivities of the rest of the food constituents in the thermal conductivity models [9, 75]. Tchigeov [76] proposed Eq. (23) for calculation of the

mass fraction of ice ( $x_{ice}$ ) in frozen food applicable to a wide variety of foods with satisfactory accuracy within range  $-45\text{ °C} \leq T \leq T_f$  and  $-2 \leq T_f \leq -0.4\text{ °C}$  [77].

$$x_{ice} = \frac{1.105x_{wo}}{\left(1 + \frac{0.7138}{\ln(T_f - T + 1)}\right)} \quad (23)$$

where  $x_{wo}$  is the mass fraction of water in the unfrozen food,  $T_f$  is initial freezing point of food (°C), and  $T$  is food temperature (°C).

### Predicting the thermal conductivity of fruit

Generally, food materials are non-homogeneous, varying in composition and structure not only between products, but also within a single product. Estimating the thermal properties of foods based on composition requires detailed knowledge of the mass fractions of the various food components. Constituents commonly found in fruit include water, protein, fat, carbohydrate, fibre, and ash. Standard laboratory gravimetric techniques can be used to determine the component mass fractions. Alternatively, publications such as Holland et al. [78] and USDA [79] state typical compositions for a wide range of food materials and food products. In conjunction with such composition data, the Choi and Okos [80] model has been used to predict the thermophysical properties of the constituents as function of temperature. Then, the estimation of the thermal properties of a food product is made by taking into account the mass average of the components and the structure of the food material (i.e., how the different constituents are structured in space inside the food).

In this regard, the parallel or perpendicular models Eqs. (24) and (26) are used to estimate the thermal conductivity of food, based on analogies with electrical resistance [81]. The two models have been used to predict the upper and lower bounds of thermal conductivities of most foods [74, 75]. The parallel model is a summation of the thermal conductivities of the food constituents multiplied by their volume fractions (Eq. (24)).

$$k = \sum x_i^v k_i \quad (24)$$

where  $x_i^v$  is the volume fraction of the constituent  $i$ , calculated using Eq. (25), where  $\rho_i$  is the density of the constituent  $i$  (kg m<sup>-3</sup>):

$$x_i^v = \frac{x_i / \rho_i}{\sum (x_i / \rho_i)} \quad (25)$$

The perpendicular model is a reciprocal of the sum of volume fractions divided by their thermal conductivities (Eq. 26).

**Table 4** Summary of different methods used in the determination of thermal properties and density of fruit

| Method                                  | Measured property                                                     | Operating principle                                                                                                                                                                                                                                                                                      | Limitations                                                                                                                                               | Additional comment                                                                                                                                                                                                              | Reference(s)                         |
|-----------------------------------------|-----------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------|
| Transient line heat source method       | Specific heat capacity<br>Thermal conductivity<br>Thermal diffusivity | Temperature change of the wire heated by a controlled source (heat pulse) and embedded in the test material for a particular time period is dependent on the material thermal properties                                                                                                                 | Free convection due to probe heating in high moisture foods could give erroneous results<br>Probe sizes may not be suitable for some fruit or fruit parts | Most suited for fruit<br>Fast method<br>High accuracy<br>Works well at high pressure measurements                                                                                                                               | [3, 43, 49, 50, 57, 58, 66, 128–129] |
| Method of mixtures                      | Specific heat capacity                                                | The specific heat is determined from the heat exchange balance after the sample is dropped in the calorimeter and equilibrium temperature is achieved. Heat loss from the measured substance = to the heat gain by water                                                                                 | Method assumes that heat loss that is not accounted for is negligible<br>Needs a calibration run with reference material of known heat capacity           | Modern calorimeters have an adiabatic jacket to minimise heat exchange of the calorimeter and its surroundings<br>It's a simple and accurate method                                                                             | [41, 50, 122]                        |
| Differential Scanning Calorimetry (DSC) | Specific heat capacity                                                | Heat flow rate to the sample programmed in a specified environment is monitored vs. time or temperature. The area under the thermogram (heat flow against temperature) generated by the system recorder is proportional to the heat energy absorbed or lost by product in the heating or cooling process | Uses very small sample sizes<br>Expensive equipment                                                                                                       | Can scan a wide range of temperatures<br>Suitable for the determination of the effect of temperature on specific heat of foods in short time                                                                                    | [41, 43, 44, 47, 49, 130, 131]       |
| Thermal diffusivity tube                | Thermal diffusivity                                                   | Based on the analytical solution for the heat diffusion equation in a long cylinder                                                                                                                                                                                                                      | Suitable for fruit pulps but not whole fruit                                                                                                              | Cylinder filled with sample, with thermocouple at thermo-centre is placed in a temperature gradient, then temperature is recorded throughout the experiment. Then temperature and time is correlated through an exponential fit | [29, 49, 51, 132, 133]               |
| Cylindrical cells method                | Thermal conductivity<br>Specific heat                                 | Conduction inside the cell is described by the Fourier equation in cylindrical coordinates, with boundary conditions corresponding to heat transfer between two concentric cylindrical surfaces kept at constant temperature                                                                             | Suited for liquid samples                                                                                                                                 | The liquid whose properties are being determined fills two concentric cylinders 180 mm in length, separated by an annular space of 2 mm                                                                                         | [59, 132, 134]                       |
| Pycnometry                              | True density                                                          | Pycnometer, a calibrated flask that allows weighing of known volume of liquid                                                                                                                                                                                                                            | Best suited for liquid samples                                                                                                                            | Measurements can be made at different temperature in a water bath                                                                                                                                                               | [5, 52, 132]                         |

Table 4 (continued)

| Method                         | Measured property | Operating principle                                                                                                                                                                                                            | Limitations                                                                                                                                                                                                                              | Additional comment                                                                                                                                                                                                                                                     | Reference(s) |
|--------------------------------|-------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------|
| Gas stereopycnometer           | True density      | Balance of pressure and volume of gases in 2 chambers, one with fruit and the other without, using the ideal gas law                                                                                                           | No significant change in moisture content should occur during the measurement<br>Ideal for dry fruit only<br>Small variations in gas pressure inside the sample chamber may give rise to significant errors in the measurement of volume | A pre-weighed fruit is placed in a sample holder of known volume, outgassed with helium gas, pressure is recorded. Helium is then introduced into 2nd chamber of known volume and pressure is recorded too<br>Method is accurate but requires very precise calibration | [135, 136]   |
| Volumetric displacement method | Apparent density  | Relationship between weight and Volume of water displaced in graduated cylinder<br>Buoyant force method is based on the Archimedes principle, the sample is weighed inside and outside of an immersion liquid of known density | Sample should remain suspended in the liquid, not absorb liquid and not touch the bottom or the sides of the container                                                                                                                   | Easy and cheap method<br>Applicable to samples of any shape<br>Presence of air bubbles can cause error                                                                                                                                                                 | [2, 136]     |

$$k = \frac{1}{\sum (x_i^v/k_i)} \quad (26)$$

The density of food material can be estimated based on the mass fractions of the individual components using Eq. (27):

$$\rho = \frac{1 - \varepsilon}{\sum (x_i/\rho_i)} \quad (27)$$

where  $\varepsilon$  is the food porosity,  $x_i$  is the mass fraction of the individual food constituents and  $\rho_i$  is the density of the food constituents ( $\text{kg m}^{-3}$ ).

Earlier models used to predict thermal conductivity of food items include methods like dilute dispersion of small spheres in a continuous phase [82] (Eq. 28), Levy [83] and the Kopelman [84] models. The models consider two distinct phases of the food materials. When foods contain more than two distinct phases, the models must be applied successively when determining thermal conductivities of such food materials [75].

$$k = k_c \frac{1 - [1 - a(k_d/k_c)]b}{1 + (a - 1)b} \quad (28)$$

where  $k$  is the thermal conductivity of mixture ( $\text{W m}^{-1} \text{K}^{-1}$ ),  $k_c$  is thermal conductivity of continuous phase ( $\text{W m}^{-1} \text{K}^{-1}$ ),  $k_d$  is thermal conductivity of dispersed phase ( $\text{W m}^{-1} \text{K}^{-1}$ ),  $a$  is  $3k_c/(2k_c + k_d)$ ,  $b$  is  $V_d/(V_c + V_d)$ , where  $V_d$  is volume of dispersed phase ( $\text{cm}^3$ ) and  $V_c$  is volume of continuous phase ( $\text{cm}^3$ ).

Levy [83] modified Eq. (28) to derive Eq. (29) for thermal conductivity determination

$$k = k_c \frac{k_2[(2 + \Lambda) + 2(\Lambda - 1)F_1]}{(2 + \Lambda) - (\Lambda - 1)F_1} \quad (29)$$

where  $\Lambda$  is the thermal conductivity ratio ( $\Lambda = k_1/k_2$ ),  $k_1$  and  $k_2$  are thermal conductivities of food components (phases) 1 and 2, respectively. While

$$F_1 = 0.5 \left\{ \left( \frac{2}{\sigma} - 1 + 2R_1 \right) - \left[ \left( \frac{2}{\sigma} - 1 + 2R_1 \right)^2 - \frac{8R_1}{\sigma} \right]^{0.5} \right\} \quad (30)$$

where

$$\sigma = \frac{(\Lambda - 1)^2}{(\Lambda + 1)^2 + (\Lambda/2)} \quad (31)$$

and  $R_1$  is the volume fraction of component 1 (Eq. 32)

$$R_1 = \left[ 1 + \left( \frac{1}{x_1} - 1 \right) \left( \frac{\rho_1}{\rho_2} \right) \right]^{-1} \quad (32)$$

Here,  $x_1$  is the mass fraction of component 1,  $\rho_1$  and  $\rho_2$  are densities ( $\text{kg m}^{-3}$ ) of components 1 and 2, respectively.

Kopelman [84] developed several expressions for thermal conductivity for homogeneous and fibrous foods: For homogeneous food materials: (a) for an isotropic, two-component system composed of continuous and discontinuous phases, in which thermal conductivity is independent of direction of heat flow and the thermal conductivity of the continuous phase is assumed to be much larger than that of the discontinuous phase (Eq. 33).

$$k = k_c \left[ \frac{1 - L^2}{1 - L^2(1 - L)} \right] \quad (33)$$

(b) as in (a) but the thermal conductivity of the discontinuous phase is much higher than that of the continuous phase, Eq. (34) is used to determine the thermal conductivity of the mixture

$$k = k_c \left[ \frac{1 - [1 - M]}{1 - M(1 - L)} \right] \quad (34)$$

where  $k_c$  is the thermal conductivity of the continuous phase ( $\text{W m}^{-1} \text{K}^{-1}$ ) and  $L$  is the volume fraction of the discontinuous phase,  $M = L^2(1 - k_d/k_c)$  and  $k_d$  and  $k_c$  is the thermal conductivity of the discontinuous and continuous phases ( $\text{W m}^{-1} \text{K}^{-1}$ ), respectively.

For fibrous food materials, thermal conductivity depends on the direction of heat flow relative to the food fibres [85]: (a) for heat flow parallel to the food fibres (Eq. (35))

$$k_{\parallel} = k_c \left[ 1 - N^2 \left( 1 - \frac{k_d}{k_c} \right) \right] \quad (35)$$

(b) For heat flow perpendicular to the food fibres (Eq. (36))

$$k_{\perp} = k_c \left[ \frac{1 - P}{1 - P(1 - N)} \right] \quad (36)$$

where  $N$  is the volume fraction of the discontinuous phase,  $P = N(1 - k_d/k_c)$ .

Table 5 lists thermal conductivity, thermal diffusivity and density models for fruit or fruit groups from experimental studies in literature. While some models are only based on the water content of the fruit, others are based on the temperature of the fruit at that particular time, while the rest consider both temperature and water content of the fruit for thermal property prediction. These models are listed in that order (water content, temperature, water content + temperature) in Table 5.

### Predicting the specific heat capacity of fruit

The specific heat capacity of a food item at temperatures above its initial freezing point can be obtained based on generalized predictive models for specific heat capacity of foods

based on composition as given by the Choi and Okos [80] model (Eq. (37)).

$$C_P = \sum C_{pi} x_i \quad (37)$$

where  $C_{pi}$  is the specific heat capacity of the individual food components ( $\text{kJ kg}^{-1} \text{K}^{-1}$ ) and  $x_i$  is the mass fraction of the food components. In the absence of detailed composition of a food, Chen [42] proposed a simpler model (Eq. 38) based on the mass fractions of solids ( $x_s$ ) in the unfrozen food item.

$$C_P = 4190 - 2300x_s - 628x_s^3 \quad (38)$$

Below freezing point, Eq. (39) [85] and Eq. (40) [42] can be used to predict the apparent specific heat of the frozen material. Apparent specific heat considers the sensible heat from temperature change and latent heat from fusion of water to make ice [74, 75].

$$C_a = C_f + (x_{wo} - x_b) \left[ \frac{L_o(t_o - t_f)}{t_o - t} \right] \quad (39)$$

$$C_a = 1.55 + 1.26x_s - \frac{x_s R T_o^2}{M_s t^2} \quad (40)$$

where  $C_a$  is the apparent specific heat ( $\text{kJ kg}^{-1} \text{K}^{-1}$ ),  $C_f$  is specific heat of fully frozen food ( $\text{kJ kg}^{-1} \text{K}^{-1}$ ),  $x_{wo}$  is mass fraction of water above initial freezing point,  $x_b$  is mass fraction of bound water,  $L_o$  is latent heat of fusion of water ( $\text{kJ kg}^{-1}$ ),  $t_o$  is freezing point of water ( $^{\circ}\text{C}$ ),  $t_f$  is initial freezing point of food ( $^{\circ}\text{C}$ ),  $t$  is food temperature ( $^{\circ}\text{C}$ ),  $x_s$  is mass fraction of solids,  $R$  is universal gas constant,  $T_o$  is freezing point of water ( $^{\circ}\text{C}$ ) and  $M_s$  is relative molecular mass of soluble solids in food.

Simple linear models such as Siebel model [86] have also been used to predict specific heat capacity of foods. These equations are obtained from curve fitting of experimental data. Table 6 lists some examples of models in this category. Similar to thermal conductivity models, while some of the models consider water content of the fruit temperature only, other models are based on the temperature of the fruit, while the rest are based on both water content and the fruit temperature.

## Respiration and transpiration behaviours of fruit

### Respiration of fruit

The respiration and transpiration activities of produce are crucial considerations in designing and operating thermal processes. Respiration is an enzymatic process by which

**Table 5** Prediction equations for thermal conductivity, thermal diffusivity, and density of fruit based on temperature and moisture content

| Property             | Prediction equation                                                                               | Type of model                                | Units                              | Fruit                | Limitations                                                 | R <sup>2</sup> | Reference(s) |
|----------------------|---------------------------------------------------------------------------------------------------|----------------------------------------------|------------------------------------|----------------------|-------------------------------------------------------------|----------------|--------------|
| Thermal conductivity | $k = 0.148 + (0.00493 W)$                                                                         | Linear regression                            | $W m^{-1} ^\circ C^{-1}$           | Fruit & vegetables   | Limited to water contents > 60% and fruit denser than water | –              | [57]         |
|                      | $k = 0.283 - 0.256^{-0.256 W}$                                                                    | Least square correlation                     | $Btu ft^{-1} h^{-1} ^\circ F^{-1}$ | Apple (cv. Grany S)  | –                                                           | 0.967          | [127]        |
|                      | $k = 0.27 + 0.0037 W$                                                                             | Linear regression                            | $W m^{-1} K^{-1}$                  | Plum                 | –                                                           | 0.98           | [122]        |
|                      | $k = -0.035 + 0.0085 W$                                                                           | Linear regression                            | $W m^{-1} K^{-1}$                  | Nectarine            | –                                                           | 0.95           | [122]        |
|                      | $k = 0.11 + 0.0053 W$                                                                             | Linear regression                            | $W m^{-1} K^{-1}$                  | Peach                | –                                                           | 0.99           | [122]        |
|                      | $k = 0.084 + 0.546 \frac{W}{1+W} + 0.0059T$                                                       | Linear regression                            | $W m^{-1} K^{-1}$                  | Mango pulp           | –                                                           | 0.993          | [59]         |
|                      | $k = 0.003(T - 273.15) + 0.2762$                                                                  | Linear Regression                            | $W m^{-1} K^{-1}$                  | Apple (cv. Jonathan) | 273–333 K                                                   | 0.9989         | [55]         |
|                      | $k = 0.0031(T - 273.15) + 0.2826$                                                                 | Linear Regression                            | $W m^{-1} K^{-1}$                  | Apple (cv. Golden D) | 273–333 K                                                   | 0.9967         | [55]         |
|                      | $k = 0.003(T - 273.15) + 0.3337$                                                                  | Linear Regression                            | $W m^{-1} K^{-1}$                  | Apple (cv. Jonagold) | 273–333 K                                                   | 0.9902         | [55]         |
|                      | $k = (0.232 \pm 0.003) + (0.359 \pm 0.004)W + ((1.1 \pm 0.02) \times 10^{-3})T$                   | Linear polynomial                            | $W m^{-1} ^\circ C^{-1}$           | Passion fruit juice  | –                                                           | 0.996          | [35]         |
|                      | $k = 0.459 - 7.2 \times 10^{-3} T - 2.5 \times 10^{-3} W + 1.7 \times 10^{-4} TW$                 | Linear regression                            | $W m^{-1} K^{-1}$                  | Mango                | 60–100 °C                                                   | 0.823          | [49]         |
|                      | $k = 0.099 - 9.0 \times 10^{-3} T + 0.010 W + 4.9 \times 10^{-4} T^2$                             | Linear regression                            | $W m^{-1} K^{-1}$                  | Mango                | – 10 to – 30 °C                                             | 0.908          | [49]         |
|                      | $k = 0.0797 + 0.5238 W + 0.00058 T$                                                               | Linear regression                            | $W m^{-1} ^\circ C^{-1}$           | Orange juice         | –                                                           | 0.97           | [132]        |
| Thermal diffusivity  | $\alpha = 0.1273 + 0.0003 T + 4E-06T^2$                                                           | 2 <sup>nd</sup> order polynomial correlation | $10^6 m^2 s^{-1}$                  | Tomato puree         | 20–130 °C                                                   | 0.995          | [44]         |
|                      | $a = 0.0068(T - 273.15) + 0.9968$                                                                 | Linear Regression                            | $10^7 m^2 s^{-1}$                  | Apple (cv. Idared)   | 273–333 K                                                   | 0.9979         | [55]         |
|                      | $a = 0.0047(T - 273.15) + 1.0292$                                                                 | Linear Regression                            | $10^7 m^2 s^{-1}$                  | Apple (cv. Jonathan) | 273–333 K                                                   | 0.9907         | [55]         |
|                      | $a = 0.0057(T - 273.15) + 1.0005$                                                                 | Linear Regression                            | $10^7 m^2 s^{-1}$                  | Apple (cv. Golden D) | 273–333 K                                                   | 0.9952         | [55]         |
|                      | $a = 0.0053(T - 273.15) + 1.1127$                                                                 | Linear Regression                            | $10^7 m^2 s^{-1}$                  | Apple (cv. Jonagold) | 273–333 K                                                   | 0.9819         | [55]         |
|                      | $\alpha \times 10^7 = 3.921 - 0.058 T - 0.024 W + 4.7 \times 10^{-4} TW + 2.1 \times 10^{-4} T^2$ | Linear regression                            | $m^2 s^{-1}$                       | Mango                | 60–100 °C                                                   | 0.943          | [49]         |
|                      | $\alpha \times 10^7 = 0.026 - 0.232 T + 0.041 W - 1.3 \times 10^{-4} TW - 5.3 \times 10^{-3} T^2$ | Linear regression                            | $m^2 s^{-1}$                       | Mango                | – 10 to – 30 °C                                             | 0.932          | [49]         |
|                      | $\alpha_{exp} = 7.9683 \times 10^{-8} + 5.9839 \times 10^{-8} W + 0.0215 \times 10^{-8} T$        | Linear regression                            | $10^{-7} m^2 s^{-1}$               | Orange juice         | –                                                           | 0.97           | [132]        |
|                      | $\rho = \frac{\rho_w}{(0.599 \pm 0.004) + (0.421 \pm 0.006)W}$                                    | Linear polynomial                            | $kg m^{-3}$                        | Passion fruit juice  | –                                                           | 0.991          | [35]         |
|                      | $\rho = 0.636 + 0.102 \ln W$                                                                      | Least square correlation                     | $g cm^{-3}$                        | Apple (cv. Grany S)  | –                                                           | 0.978          | [127]        |
| Density              | $\rho = 1206 + 110 \left( \frac{M_w}{M_{w0}} \right) - 260 \left( \frac{M_w}{M_{w0}} \right)^2$   | Empirical model                              | $kg m^{-3}$                        | Plum                 | –                                                           | 0.87           | [122]        |
|                      | $\rho = 677 + 812 \left( \frac{M_w}{M_{w0}} \right) - 477 \left( \frac{M_w}{M_{w0}} \right)^2$    | Empirical model                              | $kg m^{-3}$                        | Peach                | –                                                           | 0.87           | [122]        |
|                      | $\rho = 867 + 585 \left( \frac{M_w}{M_{w0}} \right) - 411 \left( \frac{M_w}{M_{w0}} \right)^2$    | Empirical model                              | $kg m^{-3}$                        | Nectarine            | –                                                           | 0.87           | [122]        |
|                      | $\rho = 1428.5 - 454.9 W - 0.231 T$                                                               | Linear regression                            | $kg m^{-3}$                        | Orange juice         | –                                                           | 0.97           | [132]        |
|                      | $\rho = (686 \pm 21) + (1008 \pm 10)^{(-1.2 + 0.1)W} - (0.55 \pm 0.01)T$                          | Linear polynomial                            | $kg m^{-3}$                        | Passion fruit juice  | –                                                           | 0.999          | [35]         |
|                      | $\rho = 1417 - 453.2 \frac{W}{1+W} + 0.1878T$                                                     | Linear regression                            | $kg m^{-3}$                        | Mango pulp           | –                                                           | 0.995          | [59]         |

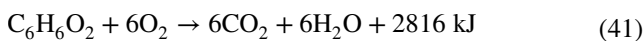
$T$ =temperature (°C, except for [55] in K),  $W$ =Water content (w/w (wet basis) except for [60] and 129 on dry basis, [49] and Sweat et al. (1974) on %),  $M_w/M_{w0}$ =moisture content ratio from initial ( $M_{w0}$ ) to moisture content at measurement time ( $M_w$ )

**Table 6** Prediction equations for specific heat capacity of fruit

| Prediction equation                            | Units                             | Fruit                | Temp range (K)  | R <sup>2</sup> | Reference(s) |
|------------------------------------------------|-----------------------------------|----------------------|-----------------|----------------|--------------|
| $C_p = 0.837 + 3.349 W$                        | $\text{kJ kg}^{-1} \text{K}^{-1}$ | All foods            | –               | –              | [86]         |
| $C_p = 1.382 + 2.805 W$                        | $\text{kJ kg}^{-1} \text{K}^{-1}$ | All foods            | $T \geq T_{cr}$ | –              | [25]         |
| $C_p = 2.11 + 0.0017 W$                        | $\text{kJ kg}^{-1} \text{K}^{-1}$ | Plum                 | –               | 0.99           | [122]        |
| $C_p = 2.89 + 0.012 W$                         | $\text{kJ kg}^{-1} \text{K}^{-1}$ | Nectarine            | –               | 0.90           | [122]        |
| $C_p = 2.53 + 0.017 W$                         | $\text{kJ kg}^{-1} \text{K}^{-1}$ | Peach                | –               | 0.99           | [122]        |
| $C_p = 10.581 (T - 273.15) + 2891.3$           | $\text{kJ m}^{-3} \text{K}^{-1}$  | Apple (cv. Golden D) | 273–333         | 0.99           | [55]         |
| $C_p = 9.0199 (T - 273.15) + 3060.9$           | $\text{kJ m}^{-3} \text{K}^{-1}$  | Apple (cv. Jonagold) | 273–333         | 0.99           | [55]         |
| $C_p = 3913.5 + 1.016 T - 0.0017 T^2$          | $\text{J kg}^{-1} \text{K}^{-1}$  | Tomatoes             | 293–403         | 0.94           | [44]         |
| $C_p = 1.00802 + 0.01897 W + 0.001188 T$       | $\text{kJ kg}^{-1} \text{K}^{-1}$ | Berberis             | –               | 0.99           | [50]         |
| $C_p = 1.119 + 3.274 \frac{W}{1+W} + 0.00152T$ | $\text{kJ kg}^{-1} \text{K}^{-1}$ | Mango pulp           | –               | 0.99           | [59]         |
| $C_p = 1424.34 + 2673.19 X_W + 2.446 T$        | $\text{J kg}^{-1} \text{K}^{-1}$  | Orange juice         | –               | 0.97           | [132]        |

$T$ =temperature ( $^{\circ}\text{C}$ , except for [55] in K),  $W$ =water content (w/w (wet basis) except for [60] on dry basis, and Aghbashlo et al. (1974) on %).  $T_{cr}$ =freezing temperature ( $^{\circ}\text{C}$ )

fruit cells convert sugars and oxygen into carbon dioxide, water, and heat—heat of respiration (Eq. 41). This heat of respiration contributes to the total cooling load in cold chain operations [87]. Exhaustion of the sugar reserves from the fruit leads to senescence (ageing) and then death or decay of the fruit. Proper ventilation of packaged produce and gas control in modified and controlled atmosphere packaging prevent these unwanted changes [88–92].



Fruit are classified as either climacteric or non-climacteric based on their respiratory patterns. Climacteric fruit can be harvested at maturity stage but before ripening, at this stage respiration is minimum. They experience a respiratory climacteric characterised by a rapid rise in respiratory rate at start of ripening that slows down when the fruit is fully ripe [87]. During ripening, climacteric fruit produce a lot of ethylene, thus ethylene treatment is used to control the rate and uniformity of ripening of climacteric fruit [93]. Examples include apple, pear, bananas, peach, plums, tomatoes etc. Non-climacteric fruit ripen only when still attached to the parent plant. Their sugar acid content does not increase once detached from the plant. Their respiration rates progressively slow down as they grow and after harvest. Non-climacteric fruit produce very little ethylene and do not respond to ethylene ripening treatment [94]. Examples include berries, citrus, pomegranate, pineapple, etc.

Respiration rate can be calculated from carbon dioxide evolution and oxygen consumption as in Eqs. (42) and (43), respectively [90]. The percentages of these gases are measured by taking head space gas concentration of fruit samples in closed jar (closed system method of determining fruit respiration).

$$R_{\text{CO}_2} = \frac{V_f}{W} \frac{(y_{\text{CO}_2} - y_{\text{CO}_2}^i)}{(t - t_i) \times 100} \quad (42)$$

$$R_{\text{O}_2} = \frac{V_f}{W} \frac{(y_{\text{O}_2}^i - y_{\text{O}_2})}{(t - t_i) \times 100} \quad (43)$$

where  $R_{\text{CO}_2}$  and  $R_{\text{O}_2}$  is the carbon dioxide production rate and oxygen consumption rate ( $\text{ml kg}^{-1} \text{h}^{-1}$ ), respectively,  $V_f$  is the free volume in the jar minus volume occupied by fruit (ml),  $W$  is weight of fruit (kg),  $y_{\text{CO}_2}$  and  $y_{\text{CO}_2}^i$  are concentration of carbon dioxide (%) at time  $t$  (h) and initial time—time zero,  $t_i$  (h), respectively, and  $y_{\text{O}_2}$  and  $y_{\text{O}_2}^i$  are concentration of oxygen (%) at time  $t$  (h) and initial time—time zero,  $t_i$  (h), respectively.

The respiratory heat is then determined from Eq. (44) [96, 97]

$$Q_r = \left( \frac{2816}{6} \right) \times \left( \frac{R_{\text{CO}_2} + R_{\text{O}_2}}{2} \right) \xi \quad (44)$$

where  $Q_r$  is the heat of respiration ( $\text{J kg}^{-1} \text{h}^{-1}$ ),  $\xi$  is the amount of heat produced out of the total respiration energy.  $\xi$  varies between 0.8 and 1.0 [97]. Table 7 gives a list of the respiration heat of selected fruit from literature at  $20^{\circ}\text{C}$ .

## Fruit transpiration

Transpiration (moisture loss) in fruit involves the transport of moisture through the skin of the commodity, evaporation of this moisture from the commodity surface and the convective mass transport of the moisture to the surrounding. Excessive moisture loss leading to shrivel is a main

**Table 7** Heat of respiration of fruit at 20 °C

| Fruit        | Heat of respiration (mW kg <sup>-1</sup> ) | References |
|--------------|--------------------------------------------|------------|
| Avocado      | 218.7–1029.1                               | [137]      |
| Strawberries | 303.1–581.0                                | [137, 138] |
| Blueberries  | 153.7–259.0                                | [137]      |
| Pears        | 89.2–207.6                                 | [137]      |
| Apples       | 50.0–103.8                                 | [137]      |
| Grapes       | 97.0                                       | [137, 139] |
| Plums        | 53.3–77.1                                  | [140]      |
| Water melon  | 51.4–74.2                                  | [137, 141] |

challenge in fresh fruit markets affecting saleable weight, appearance, texture, nutritional quality and fruit flavour [1, 95].

The rate at which fruit under storage lose moisture is dependent on the prevailing vapour pressure deficit in the surrounding atmosphere, rate of air movement around the produce, fruit surface area to volume ratio, skin structure, heat of respiration, maturity level, and number of pores on fruit surface [87]. Equation (45) gives a simple model for moisture transport [87, 97].

$$M = k_t(P_s - P_a) \quad (45)$$

where  $M$  is the transpiration rate (mg kg<sup>-1</sup> s<sup>-1</sup>),  $k_t$  the transpiration coefficient of particular fruit (mg kg<sup>-1</sup> s<sup>-1</sup> Pa<sup>-1</sup>),  $P_a$  ambient vapour pressure (Pa), and  $P_s$  evaporative vapour pressure (Pa). The transpiration coefficient represents the reciprocals of resistance of moisture transfer, this resistance depends on the surface structure of the fruit, fruit respiration and dissolved substances in the fruit water [97, 98].

Energy to drive moisture from the fruit surface is both internal (heat of respiration) and external (convective heat from fruit surrounding), this is shown in Eq. (47) [95]. The internal and external heat energies are used for latent heat of moisture evaporation and sensible heat of fruit temperature change [95]. This heat balance is shown in Eq. (48) [96].

$$L_m = \frac{Q_r W + hA(T_a - T_p)}{\lambda} \quad (47)$$

$$Q_r W + hA(T_a - T_p) = L_m \lambda + W C_p \frac{\partial T_p}{\partial t} \quad (48)$$

where  $L_m$  is the rate of moisture evaporation from produce (kg h<sup>-1</sup>),  $Q_r$  is the respiratory heat (J kg<sup>-1</sup> h<sup>-1</sup>),  $W$  is the weight of fruit (kg),  $h$  is the convective heat transfer coefficient of the fruit (J m<sup>-2</sup> °C<sup>-1</sup> h<sup>-1</sup>),  $A$  is the surface area of fruit (m<sup>2</sup>),  $T_a$  is ambient temperature (°C),  $T_p$  fruit temperature (°C),  $\lambda$  is the latent heat of moisture evaporation (J kg<sup>-1</sup>),  $C_p$  is specific heat of fruit (J kg<sup>-1</sup> °C<sup>-1</sup>), and  $t$  is time

(h). Predicting moisture loss of produce and associated heat production/loss is crucial for the proper design of postharvest handling processes, packaging and predicting the fresh life of fresh produce [95, 96].

## Conclusion and future prospects

The thermal properties of fruit are important in the design and operation of cold storage rooms and refrigerated transport equipment as well as in the estimation of process times for precooling, refrigeration, freezing, heating and drying of fruit and fruit products. The transient line heat source method, that makes use of wires and probes, is the preferred measurement technique for fruit thermal properties.

Generally, measured thermal property values vary considerably with temperature and moisture content of the fruit. Hence, care should be taken in reading property data from literature. Given the high variability of biological materials, accurate measurement of the thermal properties of fruit is a difficult task. Therefore, the most viable option is to predict these thermal properties using correlation equations (existing in the literature) that account for the effects of chemical composition and temperature. There are a variety of correlation equations to predict fruit thermal properties. The Choi and Okos correlations are the most widely used models. However, one should evaluate the practicality of this technique considering the structure of a fruit (morphology: the size and property of seeds, mesocarp, epicarp, etc.) as a whole. The properties of the different tissue parts and their spatial arrangement determine the thermal dynamics of an individual fruit. Thus, it is recommended to take into consideration the morphology of the fruit when using thermal property data as different parts (tissues) of the fruit can affect the heat diffusion differently, creating a more complex system than assumed in the various correlation models.

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