The carrot (*Daucus carota*) is a root vegetable, usually orange, purple, red, white or yellow in color, with a crisp texture when fresh. It is a rich source of β-carotene and contains other vitamins, like thiamine, riboflavin, vitamin B-complex and minerals. *Kaur et al. (2009)* reported the consumption of carrot mainly as raw, juice, salads, cooked vegetable, sweet dishes etc. Fruit and vegetable juices have become important in recent years due to overall increase in natural juice consumption as an alternative to the traditional caffeine containing beverages such as coffee, tea, or carbonated soft drinks.

Carrot pomace is a by-product obtained during carrot juice processing. It has good residual amount of all the vitamins, minerals and dietary fibre. So far the left over pomace, received after juice extraction of carrots, does not find proper utilization. The carrot pomace contains high level of moisture, which needs to be reduced to safe storage level.

Drying of vegetables as a means of improving storability has been practiced for many centuries. As compared to fresh vegetables which can be kept for few days only under ambient conditions, dry products can be stored for months or even years without appreciable loss of nutrients. Drying of vegetables also reduces the bulk weight thus facilitating ease of transportation. In some cases drying may lead to a considerable reduction in volume and hence reduction in storage space requirements.
2.1 Drying studies on carrot and other vegetables

A number of researchers have conducted drying of fruits and vegetables, so that the moisture content can be reduced and other value added product can be prepared further.

**Pazarincevic and Baras (1970)** studied the trans beta-carotene content in fresh carrots, blanched fresh carrots and carrots dehydrated by different processes. After steam blanching for 5 min the carrots were dried by conventional air-drying at 60, 70 and 80°C, by vacuum drying at 60 and 70°C and vacuum drying at the same temperature after N₂ purging. Results indicated major decrease in trans beta-carotene content after conventional air-drying, losses being more pronounced at lower temperature and longer drying periods. The losses of trans beta-carotene at 60, 70 and 80°C was 48, 40 and 38% in blanched carrots respectively. Only 21-22% losses in vacuum drying, 7% with purging also have been reported.

**Lazer (1972)** explained the effect of superheated steam on blanching and partial drying of food. In bench tests on carrots and potatoes, single pieces (1/2 in cubes, and 1/2 in x 1/2 in x 1/4 in half cubes) were exposed to superheated steam at 290°F at velocities of 525, 725 and 1060 ft/min. Results showed little difference between heating with saturated steam and heating with superheated steam, in the range studied. The evaporation occurred linearly with time to give weight losses up to 15% in only 5 min at 1060 ft/min. Steam temperature were limited at less than 300°F for carrots and potatoes because of scorching.

**Grishin et al. (1973)** studied the kinetics of dehydrating vegetables and changes in the main chemical constituents (ascorbic acid, carotenes, essential oils, total sugars) due to drying process. It was recommended that diced carrots (cubes 5-8
mm) should be dried at 160°C. Carrots and onions were suggested to be used as basic ingredients of the snacks.

Anon (1977) suggested low temperature air drying at atmospheric pressure as an alternative to freeze-drying. The pre-frozen or just cooled product was placed in a cold stream of desiccated air to remove moisture. The carrot drying at 25, 32 and 40°F produced results comparable with commercially freeze-dried products. Pre-freezing decreased the rehydration time to 2-4 min in boiling water. It was also observed that drying was very slow at the lowest temperature.

Andreotti et al. (1981) dried diced carrots and sliced onions to 50% of their initial weight by hot air at 80° and 100° C respectively, followed by freeze-drying, and compared with conventionally freeze-dried products. The results revealed that the products occupied only about 1/2 the volume of freeze-dried products, but had similar rehydration properties except for a deeper colour. The process allows savings in energy, as well as storage, packaging and transport costs.

Camacho (1983) studied the air and freeze drying of carrot. Carrots were peeled, cut into 3 mm cubes and sulphited. Batches were then air-dried at 71° or 88°C, or freeze-dried at initial temperature of -1°, -18° or -40° C. Rehydration, density, colour, texture, beta-carotene content and flavour of the products was evaluated. It was reported that the rehydration coefficient of air dried and freeze dried carrots decreased with increasing drying temperature. The beta-carotene retention, colour, texture and flavor was reported as better in case of freeze-drying in comparison to air dried samples.

Snezhkin et al. (1983) conducted the experiments on the convective drying of 6, 8 and 10 mm cubes of carrots. Air temperature was maintained within 80-120° C,
moisture was 10 g/kg and velocity of drying air was 1 m/s. Drying of carrots in industrial driers UTS-1, SV-32, SPK-4G-45, SPK-4G-90 was lasted about 35-45 min to remove osmotically bonded water. The hygroscopically bonded water was also removed. It was observed that the drying intensity was independent of air temperature, but was affected by the technological properties of the material. The temperature of air velocity for second phase was recommended within 70-80°C.

Maguer and Mazza (1986) studied the effect of drying of carrot in vibro fluidizer. Fancy carrots were held at 1-2°C, 95-98% RH for 1 month, then mechanically peeled and diced, and dried in a vibro fluidizer under various temperature conditions. 3 air flow rates (5.5, 8.1 and 10.3 m³/min) and 3 loading ratios (8, 16 and 32 kg/m²) of drying area were used. Influence of air temperature on drying rates was reported.

Mulet (1987) observed the effect of air flow rate (1000-9000 kg/m²h) on kinetics of drying of 10 mm x 10 mm x 10 mm carrot cubes. For flow rates greater than 6000 kg/m²h, the value of D/r² (where D = apparent diffusivity and r = half the thickness of the cube) remained almost constant, indicating that the higher air flow rates had no influence on the drying rate.

Mulet et al. (1989) proposed three models of varying complexity to describe the falling rate period of the carrot drying process, taking shrinkage into consideration. A moving or fixed boundary problem, and constant or local moisture and temperature, dependent effective diffusivity are considered. The moving boundary problem was solved by an explicit finite difference method. Heat transfer coefficient and effective diffusivity were also determined. The expressions for effective diffusivity were developed considering the temperature for two models and local moisture and shrinkage for third model.
Mulet (1994) analyzed four diffusive models of differing complexities considered for the description of convective drying of particulate vegetables (carrots and potatoes). The relation of the degree of complexity and shrinkage, heat transfer and particle temperature variation during drying was discussed. The dependence of effective diffusivity on moisture and temperature was also studied. The effect of shrinkage was reported in establishing reliable values for De.

Domagala et al. (1996) investigated the kinetics of drying carrot cubes (10 mm and 14 mm) and slices (3 mm thick, 18.4-41.5 mm diameter) in an industrial pentabelt. The temperatures of drying air supplied under the first and second belts of the dryer were 90°C and 60°C respectively. The carrot was dried to a final moisture content of 0.1 kg/kg (9.09%). The drying curve and drying rate curve were determined. The times of the constant drying rate period were 60 and 82 min for the 10 and 14 mm cubes, respectively, and 94 min for slices. The respective total drying times were 305, 350 and 250 min.

Litvin et al. (1998) determined the optimal conditions for drying of carrot slices using a combination of an initial period of freeze drying, a short microwave treatment and a final period of vacuum or air drying. A 2 h freeze drying at a plate temperature of 30°C followed by 2 h at 55°C reduced the moisture content of carrot slices to about 40%. Subsequent microwave treatment (50 s) and vacuum or air drying reduced the moisture content further to 5%. When the method was used with a final air drying step, the quality characteristics (colour, dimensions and rehydration ratio) of carrots were similar to those of carrots dried by freeze drying alone. However, when final drying was performed in a vacuum oven, the colour quality of carrots was improved and the overall quality of carrots after rehydration was similar to that of
freshly cooked carrot slices. It was concluded that the method may be useful for reducing the time, and hence the cost, of freeze drying carrots.

**Sharma et al. (2000)** studied different blanching (steam, water and microwave) and drying (cabinet and fluidized-bed-drying) methods on the stability and composition of total carotenoids in carrots. Total carotenoid losses were higher in unblanched carrots and in fluidized bed-dried samples compared to blanched and cabinet-dried samples. Regarding individual carotenoids, beta-carotene degraded at rapid rate, while lutein degraded at slower rate during storage. Development of non- enzymic browning during storage was also influenced by the blanching treatments. It was concluded that steam-blanching prior to drying of carrots minimizes loss of carotenoids compared to microwave- and water-blanching.

**Reyes et al. (2002)** analyzed the drying curves for 3 kg batches of carrot dice (9 x 9 x 3 mm) in a mechanically agitated fluidized bed drier operated at temperature of 70-160°C, air velocities of 1.1-2.2 m/s and stirring rates of 30-70 rpm. Moisture content and shrinking of diced carrot pieces were determined. Drying kinetics were modelled by Fick's second law, for which an optimal agreement with the experimental data was obtained when the effective diffusivity was determined by a correlation based on air velocity, air temperature and the dimensional less moisture content of carrot dice. Loss of carotenes was minimum, when drying was carried out at about 130°C with a drying time below 12 min.

**Machewad et al. (2003)** studied the drying properties of carrots and their suitability for producing various value added products. Chemical properties of carrots indicated their suitability for drying and the feasibility of using carrot shreds for further processing. Leaching losses were observed in reducing sugars and total sugars during pre-treatments and an adverse effect was seen on beta-carotene content in all
samples. Reconstitution ratio of dried carrot shreds was higher in pre-treated samples than untreated. Carrot shreds dried in open air had a lower reconstitution ratio. It was suggested that dried carrot shreds could be used as a base material for preparation of carrot halwa (halva).

**Basantpure et al. (2003)** conducted experiments to develop dehydrated carrot halwa and studied the effect of milk to carrot ratio, sugar, sodium metabisulphite, and temperature on the quality of dehydrated halwa. Central composite rotatable design was used at five levels of independent variables. The results showed that the rehydration ratio decreased with an increase in milk to carrot ratio, sugar and sodium metabisulphite whereas, it increased with an increase in temperature. All these variables decreased the sensory responses namely, appearance, texture, flavour and overall acceptability at quadratic level. The interaction between milk to carrot ratio with sugar, sodium metabisulphite and temperature, however, increased sensory responses. Sodium metabisulphite and temperature interaction also increased all the responses significantly. Based on individual and compromise optimization and canonical analysis, optimum conditions recommended were: milk to carrot ratio of 2, sugar 225 g/kg of carrot shred, 255 ppm sodium metabisulphite and drying air temperature of 71°C.

**Stepiri (2008)** dried carrots using the vacuum-microwave method and tested strength using an Instron 5566 with measuring heads of class 0.5. The values of the cutting and compression forces were calculated. The testing was performed on materials that were initially blanched, osmotically dehydrated, and untreated before drying. As a result of the vacuum-microwave drying, dried carrots with a moisture content within the range (3.2–3.8)% were obtained. The blanching operation resulted
in an almost two-fold increase in the dry matter resistance to compression compared to that of the dry matter obtained from initially untreated carrot.

2.2 Modelling of thin layer drying of vegetables

Drying of materials having high moisture content is a complicated process, which involves simultaneous heat and mass transfer. The materials are dried using several techniques but thin layer drying is more popular due to its faster rate in comparison to others and minimum loss of nutrients.

Thin-layer drying describes the process of drying in a single layer of sample particles. Three types of thin-layer drying models are used to describe the drying phenomenon of farm product. The theoretical model considers only the internal resistance to moisture transfer between product and heating air whereas semi-theoretical and empirical models consider only the external resistance (Midilli et al., 2002; Panchariya et al., 2002). Theoretical model needs assumptions of geometry of a typical food, its mass diffusivity and conductivity (Demirtas et al., 1998; Ece and Cihan, 1993); empirical model neglects the fundamentals of drying process and presents a direct relationship between average moisture and drying time by means of regression analysis (Ozdemir and Devres, 1999; Wang and Singh, 1978), and semi-theoretical model is a trade off between the theoretical and empirical ones, derived from simplification of Fick’s second law of diffusion or modification of the simplified model, which are widely used, such as the Lewis, Page, Modified Page, Henderson and Pabis, Logarithmic, Two term, Approximation of diffusion, Verma and Midilli-Kucuk models.

Ajibola (1989) determined the moisture equilibrium data and thin-layer drying rates for melon seeds at 40-70°C and 10-88% RH, using static gravimetric methods. A
nonlinear least-squares regression program was used, to evaluate 5 desorption
isotherm models and 3 thin-layer drying models. The modified Halsey model gave the
least standard error of estimate (0.4% for equilibrium moisture content and 4.8% for
equilibrium RH). The exponential model, in which the drying constant was a function
of temperature and RH, was adequate for predicting thin-layer drying of melon seed.

Techasena et al. (1992) studied the thin layer hot air drying of carrot and
applied to deep bed drying. Experiments on thin layer drying were carried out using
various air conditions. Then, an equation for carrot drying in a thin layer was
developed using an exponential model. Heat and mass balances of air and product
were used to predict their changing characteristics during drying. This model was
used to simulate carrot drying in a deep bed. A good agreement between experimental
and calculated values was obtained.

Diamante and Munro (1993) used solar dryer for drying sweet potato. The
drying rates were affected by the fluctuating chamber temperature. A mathematical
model for solar drying of sweet potato was derived based on the simplified form of
Fick’s diffusion. The model could satisfactorily describe the solar drying of sweet
potato slices.

Lopez et al. (1995) presented models for the kinetics of hot air drying of 2.5
mm thick potato slices. Potatoes were cleaned, peeled, sliced, blanched in boiling
water for 7 min, and soaked in 0.001% sodium bisulphite solution for 2 min. The
slices were then dried in a pilot plant at 60, 70, 80 or 85°C and air flow 0.5, 1.0 or 1.5
m/s at a drying load of 25 kg/m². Results showed that there were 2 different drying
rates; the 1st was a constant rate period lasting up to 70 min, for which equations
correlating air flow rate and heat transfer coefficient were derived, followed by a
falling rate period which could be described by Fick's equation. Dependence of moisture diffusivity on temperature was shown to follow an Arrhenius relationship.

Madamba et al. (1996) investigated the thin-layer drying characteristics of garlic slices for a temperature range 50 - 90°C, a relative humidity range 8 – 24%, and an airflow range 0.5 – 1.0 m/s. An analysis of variance (ANOVA) revealed that temperature and slice thickness significantly affected the drying rate while relative humidity and airflow rate were insignificant factors during drying. Effective diffusivity of water varied from 2 to 4.2 x 10^{-10} m^2/s over the temperature range investigated, with an energy of activation of 989 W/kg. Four mathematical models available in the literature were fitted to the experimental data, with the Page and the two-compartment models giving better predictions than the single-term exponential and Thompson’s model. The temperature dependence of the diffusivity coefficients were reported to follow Arrhenius-type relationship.

Jognson et al. (1998) studied the drying behavior, shrinkage and moisture distribution within cylindrical piece of plantain, of varying thickness, and with different air temperatures in an experimental hot air dryer. Air temperature had the greatest influence on the drying behavior. The activation energy for air drying of plantain was estimated as 38.81KJ (g.mol)^{-1}. Change in dimension was linearly related to moisture content. Fick’s diffusion equation was used to predict the distribution of moisture within the plantain piece during drying.

Karathanos (1999) identified the kinetics of drying of dehydrated agricultural products as well as the kinetics of a decomposition reaction of the constituents of the fruits, such as sugars. The drying of currants at temperatures 65±97°C for elongated times showed that the weight did not reach equilibrium even after drying for several days, due to the decomposition of solids in addition to the water evaporation. Using
the method of successive residuals, three simple first order reaction equations were found appropriate, describing the dual water evaporation/decomposition reaction phenomenon of dried fruits.

Krokida et al. (2003) examined the effect of air conditions (air temperature, air humidity and air velocity) and characteristic sample size on drying kinetics of various plant materials (potato, carrot, pepper, garlic, mushroom, onion, leek, pea, corn, celery, pumpkin, tomato) during air drying. A first-order reaction kinetics model was used, in which the drying constant was a function of the process variables, while the equilibrium moisture content of dried products within the range of 0.10–0.90 water activity at two temperatures (30 and 70°C) was fitted to GAB equation. The parameters of the model considered were found to be greatly affected by the air conditions and sample size during drying. In particular the temperature increment increased the drying constant and decreased the equilibrium moisture content of the dehydrated products.

Doymaz (2004) studied the drying kinetics of carrot cubes. Convective air drying characteristics of carrot cubes were evaluated in a cabinet dryer. Drying was carried out at 50, 60, 65, 70°C and drying data were analyzed to obtain diffusivity values from the period of falling drying rate. In the falling rate period, moisture transfer from carrot cubes was described by applying the Fick’s diffusion model, and effective moisture diffusion coefficients were calculated. Effective diffusivity increased with increase in temperature. An Arrhenius relation with an activation energy value of 28.36 kJ/mol expressed the effect of temperature on the diffusivity. Two mathematical models were fitted to the experimental data. The Page model gave better prediction than the Henderson and Pabis model and satisfactorily described drying characteristics of carrot cubes.
Lahsasni et al. (2004) examined the effect of drying air conditions on drying kinetics of the prickly pear fruit in a convective solar drier operating with an auxiliary heating system under air controlled conditions. Moreover, the prickly pear fruits were sufficiently dried in the ranges between 32 and 36°C of ambient air temperature, 50–60 °C of drying air temperature, 23–34% of relative humidity, 0.0277–0.0833 m³/s of drying air flow rate and 200–950 W/m² of solar radiation. The results were verified with good reproducibility and drying air temperature was the main factor in controlling the drying rate. The drying followed at a falling rate period only. The expression of the drying rate equation was determined empirically from the characteristic drying curve. Eight different thin layer drying models were compared on the basis of their coefficients of determination to estimate solar drying curves. The two-term model satisfactorily described the solar drying curves of prickly pear fruit with a correlation coefficient (r) of 0.9999.

Sacilik and Unal (2005) investigated the dehydration characteristics of the Kastamonu garlic in a convective hot-air dryer. The dehydration characteristics of garlic slices were examined at air temperatures of 40, 50 and 60° C and sample thicknesses of 3 and 5 mm. During the dehydration experiments, air velocity was kept stable at 0.8 m/s. The effects of air temperature and sample thickness on the dehydration characteristics and quality parameters of the dehydrated garlic slices were determined. The transport of water during dehydration was described by Fick’s equation and the effective diffusivity was between 195 and 335 µm²/s. The effect of temperature on the effective diffusivity was described by the Arrhenius-type relationship. The activation energy was found as 23.48 kJ/mol. The experimental dehydration data of garlic slices obtained were fitted to the four well-known semi-theoretical drying models, i.e. the Henderson and Pabis, two-term, Lewis and Page
models. The accuracies of the models were measured using the coefficient of determination, mean relative percent deviation, root mean square error and reduced mean square of the deviation. All four models were acceptable for describing dehydration characteristics of garlic slices. However, the two-term model was more precise for predicting dehydration characteristics based on statistical analysis.

Akgun and Doymaz (2005) studied the olive cake characterization of the thin layer drying kinetics at a wide range of drying temperatures (50 to 110°C), a constant sample thickness and air velocity of 1.2±0.03m/s in a laboratory scale dryer. Various mathematical models were used to fit the olive cake data. The logarithmic model was found to give better predictions than the others. In addition, the temperature dependence of the effective diffusivity coefficient was expressed by an Arrhenius type relationship. The effective diffusivity varied between 0.3 and 1.1 x 10^{-8} m^{2}/s with activation energy of 17.97 kJ/mol.

Marquez et al. (2006) reported the drying behavior of rose hip fruits using air of 50, 60, 70, 80°C; relative humidities, 5%, 50% and velocities, 1, 2, 3, 5 m/s. A short time predictive model for diffusion inside solids was selected to interpret the data with satisfactory accuracy. By this fitting procedure, diffusion coefficients of water in rose hips fruit were obtained as 7.501 x 10^{-11} (50°C) and 3.367 x 10^{-10} (80°C) m^{2}/s, with an activation energy of 46 kJ/mol.

Akpinar (2006) implemented mathematical modeling on thin layer drying of potato, apple and pumpkin slices in a convective cyclone dryer. In order to estimate and select the appropriate drying curve equation, 13 different models, which are semi-theoretical and/or empirical, were applied to the experimental data and compared according to their coefficients of determination (r, \chi^2), which were predicted by non-linear regression analysis using the Statistica Computer Program. Moreover, the
effects of drying air temperature, velocity and sample area on the model constants and coefficients were also studied by multiple regression analysis. Consequently, of all the drying models, a semi-theoretical Midilli–Kucuk model was selected as the best one, according to $r$ and $\chi^2$.

**Guine and Fernandes (2006)** investigated the experimental dehydration behaviour of three different varieties of chestnuts (*Castanea sativa*). The experiments were carried out under isothermal conditions, using ventilated driers at 70, 80 and 90°C. The experimental data obtained for the variations of water content along the drying time was fitted to a two-term exponential model with success. The experimental drying rate points were calculated by approximating the derivatives to finite differences and the drying rate versus moisture content and time curves were fitted, respectively, to a sigmoid function and a first-order kinetics, with relatively good results. The experimental data was used to predict effective diffusivity according to Fick’s second law equation, assuming that the variation of diffusivity with temperature could be expressed by an Arrhenius type function, and the values of diffusivity obtained ranged from 4.45E-9 to 7.65E-9 m$^2$/s, respectively for chestnuts of the variety Longal at 70°C and Viana at 90°C.

**Babalis et al. (2006)** fitted experimental data in selected mathematical thin-layer drying models, using non-linear regression analysis techniques for figs. The laboratory dryer, using ambient heated air and operating in a closed loop, was equipped with a dedicated continuous monitoring system. The temperatures and air velocities were in the range of 55–85°C 0.5–3.0 m/s respectively. The non-linear regression analysis and application of the mathematical models revealed that the two-term exponential model yielded the best predictions. Correlations expressing the two-
term exponential model constants and their dependence on the drying-air parameters were also reported.

Gornicki (2007) subjected carrot cubes to combined treatments of blanching and drying. Blanching was alternatively performed 3 min in boiling 5% brine solution, 3 min in boiling water or 6 min in boiling water. It was observed that the applied pre-treatments influenced the kinetics of drying. The mathematical model describing the course of drying of single blanched carrot cubes (not touching each other) under natural convection condition was formulated on the basis of the general theory of heat and mass transfer. The drying of carrot cubes in constant and falling rate were also observed.

Kaya et al. (2007) investigated the drying kinetics of quince slices as a function of drying conditions. Experiments were conducted at air temperatures of 35, 45 and 55°C, air velocities of 0.2, 0.4 and 0.6 m/s and relative humidity values of 40, 55 and 70%. The moisture data were fitted to Henderson and Pabis, Lewis and two-term exponential models and a good agreement was observed. In the ranges covered, the values of the effective moisture diffusivity, $D_{eff}$ were obtained between $0.65 \times 10^{-10}$ and $6.92 \times 10^{-10} \text{ m}^2/\text{s}$ from the Fick’s diffusion model. Using $D_{eff}$, the value of activation energy (Ea) was determined assuming the Arrhenius-type temperature relationship, which varied from 33.83 to 41.52 kJ/mol.

Doymaz (2007) investigated the air drying characteristics of pumpkin slices in a laboratory scale hot-air dryer. The thin-layer drying was carried out on three air temperatures of 50, 55 and 60°C at a constant air velocity of 1.0 m/s and relative humidity between 15% and 25%. Effective diffusivity and activation energy was also measured. The experimental moisture loss data were fitted to selected semi-theoretical and empirical thin-layer drying models. The mathematical models compared
according to the three statistical parameters such as the coefficient of determination ($R^2$), reduced chi-square ($\chi^2$) and root means square error (RMSE) between the observed and predicted moisture ratios. The effective diffusivity values changed from 3.88 to $9.38 \times 10^{-10}$ m$^2$/s within the given temperature range. An Arrhenius relation with an activation energy value of 78.93 kJ/mol expressed the effect of temperature on the diffusivity.

Kashaninejad et al. (2007) determined the thin-layer drying characteristics of pistachio nuts as a function of temperature, relative humidity and air velocity. Six mathematical models (Page model, modified Page model, exponential model, diffusion model, two term exponential model and Thompson model) for describing the thin-layer drying behavior of pistachio nuts were investigated. Tests were conducted using four air temperatures (25, 40, 55 and 70°C), three air velocities (0.5, 1.0 and 1.5 m/s) and two levels of relative humidity (5% and 20%) and three replications for each treatment. Out of the six models considered, Page model was found to be the most suitable for describing the drying behavior of the pistachio nuts. The drying air temperature had the greatest effect, whereas air velocity and relative humidity had a small effect on the drying kinetics of pistachio nuts. Effective diffusivity of water varied from $5.42 \times 10^{-11}$ to $9.29 \times 10^{-10}$ m$^2$/s over the temperature range studied, with an energy activation of 30.79 KJ/mol. The temperature dependence of the diffusivity coefficients was described satisfactorily by a simple Arrhenius-type relationship.

Wang et al. (2007) studied the hot air convective drying characteristics of thin layer apple pomace in a laboratory scale dryer. The drying experiments were carried out at 75, 85, 95 and 105 °C and at the air velocity of 1.20 ± 0.03 m/s. Different mathematical models were tested with the drying behavior of apple pomace.
The results indicated that the logarithmic model can present better predictions for the moisture transfer than other models; the drying process took place in two falling rate periods, the effective diffusivities in the second period were about six times greater than that in the first period. The general relationship of moisture ratio against drying duration in the thin layer convective drying of apple pomace was also developed.

**Wang et al. (2007a)** evaluated the characteristics of thin layer microwave drying of apple pomace with and without hot air pre-drying in a laboratory scale microwave dryer. The drying experiments were carried out at 150, 300, 450 and 600W, and the hot air pre-drying experiment was performed at 105°C. Ten commonly used mathematical models were tested and the results indicated that the Page model was most adequate in predicting moisture transfer for fresh and pre-dried apple pomace. Four regression equations of drying rate against drying duration or moisture were found to describe very well the drying characteristics for fresh and pre-treated apple pomace respectively. It was observed that nearly 70% of total drying time was spent to remove the latter half of moisture (wb) in the microwave drying with or without pre-drying.

**Rajkumar et al. (2007)** conducted preliminary trials for foam mat drying of alphonso mango pulp using batch type cabinet dryer. The foamed mango pulp was dried at 60°C with 1 mm foam thickness and was found to be the best. The drying study showed that the time required to dry the fresh (non-foamed) and foamed mango pulps were 75 and 35 min, respectively. The overall moisture diffusion in fresh and foam dried mango flakes was 5.3 and $9.7 \times 10^{-9}$ m$^2$/s, respectively. It was observed that the changes were comparatively lower in foam dried flakes than in non-foam dried flakes using continuous type foam mat dryer.
Mortaza et al. (2008) simulated thin-layer drying using a laboratory scale hot-air dryer of the static tray type. Fick’s second law was used as a major equation to calculate the moisture diffusivity with some simplification. The calculated value of moisture diffusivity varied from a minimum of $3.320 \times 10^{-10}$ to a maximum of $9 \times 10^{-9}$ m$^2$/s and the energy of activation ranged from 110.837 to 130.61 kJ/mol at 50°C to 70°C with drying air velocities of 0.5–2 m/s. The high value of the energy of activation for berberis fruit was related to the tissue of berberis fruit and high moisture content (about 74.28% w.b) and intensive changes in $D_{eff}$ values for a different air temperature at constant air velocity.

Chong et al. (2008) studied the drying kinetics of chempedak (Artocarpus integer) at different drying temperatures (50, 60, 70°C) and slab dimensions. The drying data were fitted to the different semi-theoretical models based on moisture ratio (MR) to predict the drying kinetics. A logarithmic model was found to be the best fit in this study for all the drying temperatures tested. Effective diffusivities were estimated from Fick’s 2$^{nd}$ law and the Arrhenius equation and was used to determine the diffusivity constant ($D_0$) and activation energy ($E_a$). The texture and color of dried product were altered significantly during drying.

Roberts et al. (2008) dried the waste grape seeds obtained from white wine processing (Riesling), red wine processing (Cab Franc), and juice processing (Concord) at 40, 50, and 60°C and constant air velocity of 1.5 m/s. Effective moisture diffusivity ranged between $1.57 \times 10^{-10}$ m$^2$/s for Riesling seeds, $2.93–5.91 \times 10^{-10}$ m$^2$/s for Concord seeds, and $3.89–8.03 \times 10^{-10}$ m$^2$/s for Cab Franc seeds. The temperature dependence of the effective diffusivity followed an Arrhenius relationship, and the activation energies were 40.14 kJ/mol for Riesling seeds,
30.45 kJ/mol for Concord seeds, and 31.47 kJ/mol for Cab Franc seeds. Page, Lewis, and Henderson–Pabis models were used to predict the drying curves.

**Chantaro et al. (2008)** studied the feasibility of using carrot peels, by-products from food industry, as a starting raw material to produce antioxidant dietary fiber powder. The effects of blanching and hot air drying (60 & 80°C) on the drying kinetics and physicochemical properties of dietary fiber powder were evaluated. The results showed that blanching had a significant effect on the fiber contents and compositions, water retention and swelling capacities of the fiber powder. In contrast, drying temperature in the selected range did not affect the hydration properties.

**Upadhyay et al. (2008)** studied the drying characteristics of carrot pomace. Pomace was dried under sun and in a tray drier at 60, 65 70, 75 and 80°C. Mathematical modelling for the drying data revealed that mechanical drying was superior to the sun drying. The retention of β-carotene increased from 9.86 to 11.57 mg/100g and ascorbic acid decreased from 22.95 to 13.53 mg/100g. Optimal drying was observed at 65°C on the basis of β-carotene and ascorbic acid retention. On the basis of $R^2$ value Page model rendered better prediction of drying data than the Lewis model.

**Miranda et al. (2009)** investigated the effect of air temperature on the physicochemical and nutritional properties and antioxidant capacity of Aloe vera. The drying kinetics of Aloe vera gel was modelled using the Wang–Singh equation, which provided a good fit for the experimental data. Analysis of variance revealed that the drying temperature exerted a clear influence on most of the quality parameters.

**Berruti et al. (2009)** studied the effects of air temperature and flow rate on the drying of cylindrical carrot samples in a tunnel dryer. The drying was carried out at
21, 42 and 56°C, and at air superficial velocities of 0.5, 0.625, 0.75 and 0.95 m/s. A simpler approximation was implemented using Crank’s surface evaporation equations to develop a model for predicting the diffusivity and mass transfer coefficient. Using this new model, an Arrhenius relation with activation energy of 31.76 kJ/mol successfully described the effect of temperature on the diffusivity.

**Hii et al. (2009)** investigated the cocoa drying kinetics and compared the quality of the dried beans produced from sun and artificial hot air drying. Drying trials were conducted in thin layer using natural sun light and by hot air inside an air ventilated oven at air temperatures of 60, 70 and 80°C. Comparison was also made against freeze-dried cocoa beans for quality assessment. Theoretical modelling was performed on the drying kinetics using Fick’s law of diffusion and to determine the effective diffusivity values. A new model was also proposed for thin layer drying. Reasonable values were obtained for the coefficient of determination ($R^2$) between the experimental and predicted moisture ratio data (range 0.9845–0.9976). Effective diffusivity values were reported within the permissible range.

**Kaya and Aydin (2009)** studied the thin-layer drying characteristics of some herbal leaves in a convective drier. Effects of the drying air parameters including temperature (35, 45 and 55°C), velocity (0.2, 0.4 and 0.6 m/s) and relative humidity (40%, 55% and 70%) on the total drying time were studied. The values of the moisture diffusivity ($D_{eff}$) ranged from between $1.744 \times 10^{-9}$ to $4.992 \times 10^{-9}$ m$^2$/s for nettle leaves and $1.975 \times 10^{-9}$ and $6.172 \times 10^{-9}$ m$^2$/s for mint leaves from the Fick’s diffusion model. Using $D_{eff}$, the values of $E_a$ were evaluated assuming the Arrhenius-type temperature relationship, which varied from 79.873 to 109.003 kJ/mol for nettle leaves and 66.873 to 71.987 kJ/mol for mint leaves.
Doyamaz and Ismail (2010) studied the effect of alkali emulsion of ethyl oleate and air temperature (60, 70 and 75 °C) on the drying characteristics of sweet cherry using a hot air dryer at a constant air velocity of 2.0 m/s. It was observed that both the alkali emulsion of ethyl oleate and air temperature affected the drying time. The drying times of pre-treated samples were 19.5–22.6% shorter than those of control samples. Five semi-theoretical thin layer models, namely, Lewis, Henderson and Pabis, Logarithmic, Page, Wang and Singh models were used for the modeling of the drying kinetics. It was concluded that Page model represented the drying characteristics better than the other models. The effective moisture diffusivity was determined by using Fick’s second law and was observed to lie between $5.683 \times 10^{-10}$ and $1.544 \times 10^{-9}$ m$^2$/s for the pre-treated and control samples.

Xiao et al. (2010) investigated the drying kinetics and quality of Monukka seedless grapes in an impingement dryer under different drying temperatures (50, 55, 60 and 65°C) and air velocities (3, 5, 7 and 9 m/s). Results indicated that the effect of drying temperature on drying time was more distinct than air velocity. The moisture effective diffusivity ranged from $1.82 \times 10^{-10}$ to $5.84 \times 10^{-10}$ m$^2$/s. The activation energy determined from Arrhenius equation was 67.29 kJ/mol. The hardness of dried Monukka seedless grapes changed from 9.53 to 17.16 N showing an increasing trend as drying temperature increased.

2.3 Raw material for extrusion studies

2.3.1 Carrot byproducts utilization

Carrot pomace is a by-product obtained during carrot juice processing. The juice yield in carrots is only 60-70%, and even up to 80% of carotene may be lost with
left over carrot pomace. The nutritional characteristics of carrot pomace have been reported by several researchers.

**Mckee and Latner (2000)** reviewed the source of dietary fibres in underutilization food produce. Fiber, however, remains an important component of the diet. Soluble dietary fiber, including pectic substances and hydrocolloids, is found naturally in foods such as fruits, vegetables, legumes and oat bran. Insoluble fiber, including cellulose and hemicellulose, is found in foods such as whole grains. Fiber supplementation has been used to enhance the fiber content of a variety of foods ranging from cereal-based products to meats, imitation cheeses and sauces. Cereals such as wheat, corn and oats were reported to enhance the fibre content, whereas fruits, vegetables and legumes were suggested to use for manufacturing of product. This article reviewed research on some of these underutilized sources of dietary fiber.

**Stoll et al. (2003)** reported the utilization of a carotene-rich functional food ingredient recovered through mechanical and enzymatic breakdown of the tissue of carrot pomace. The ingredients were used to prepare model beverages based on cloudy apple juice, aiming at sustainable carrot juice production. Contrary to synthetic beta-carotene supplements, the stability of the natural alpha- and beta-carotene in the beverages proved to be excellent after 20 and 24 weeks storage under moderate and even intense illumination at 23 and 19°C, respectively. Neither degradation nor isomerization was observed, thus confirming the extraordinary stability of carotenoids in their natural matrix. Furthermore, cloud stabilities as determined by centrifugation and real time sedimentation tests were found satisfactory.

**Chau et al. (2004)** reported the comparison of the characteristics, functional properties, and in vitro hypoglycemic effects of various carrot insoluble fiber-rich fractions. Fiber-rich fractions (FRFs) including insoluble dietary fibre (IDF), alcohol-
insoluble solid (AIS), and water-insoluble solid (WIS) were isolated from carrot pomace via different methods. The study revealed that carrot pomace was rich in insoluble FRFs (50.1-67.4 g/100 g), which were mainly composed of pectic polysaccharides, hemicellulose, and cellulose. These insoluble FRFs, especially WIS, were significantly (P < 0.05) higher functional properties, glucose-adsorption capacity, and amylase-inhibition activity than those of cellulose. The ability of these FRFs to adsorb glucose and reduce amylase activity implied that they might help control post-prandial serum glucose level. Moreover, it was shown that the yield, composition, functional properties, and in vitro hypoglycemic effects among the three FRFs would be affected by their preparation methods. The results recommended the consumption of these insoluble FRFs, especially WIS, as sources of food fibers or low calorie bulk ingredients in food applications requiring oil and moisture retention.

**Schweiggert (2004)** reported the carrot pomace as a source of functional ingredients. Utilization of carrot pomace as a source of valuable bioactive and functional compounds was discussed. Aspects considered include current underutilization of carrot pomace generated as a byproduct of carrot juice manufacture; carrot pomace as a source of carotenoids and fiber; health and functional properties associated with fiber and carotenoid compounds; processes for recovery of bioactive and functional compounds from carrot pomace; application of carrot pomace in functional foods; use of hydrolyzed carrot pomace as a functional ingredient in beverages; possibilities for obtaining bioactive saturated oligogalacturonic acids by enzymic breakdown of carrot pectin; and future potential for increasing pomace utilization.

**Nawirska and Kwasniewska (2005)** reported that the dietary fibre and its components were regarded as balast substances from vegetal food. Dietary fibre
includes a number of components, and each of them displays specific properties. The components of major importance were cellulose, hemicellulose, lignin and pectins. The objective of this study was to determine the amounts of particular dietary fibre fractions in samples containing apple, black currant, chokeberry, pear, cherry and carrot pomace. The results revealed the following pattern: in each pomace sample, pectins occurred in the smallest amounts, and the content of lignin was very high (black currant and cherry pomace) or comparatively high (pear, chokeberry, and apple and carrot pomace).

Yoon et al. (2005) reported that the enzymatic production of a soluble-fibre hydrolyzate from carrot pomace and its sugar composition. This study was conducted to determine the sugar composition of soluble dietary fiber from carrot pomace, a by-product from the carrot juice processing industry. Carrot pomace was treated with a mixture of 1% NaOH and 2% acetic acid, and the pretreated sample was hydrolyzed by edible snails crude enzyme. The supernatant portion was then treated with 85% ethanol and separated into alcohol-soluble dietary fibre (ASDF) and alcohol-insoluble dietary fibre (AIDF). AIDF increased from an initial value of 3.3 g/100 g to 41.7 g/100 g carrot pomace after 96 h of reaction. The AIDF contained rhamnose, arabinose, mannose, galactose, glucose and a small amount of xylose. Monosaccharides (glucose, fructose, galactose, arabinose), cellooligosaccharides (cellopentaose, cellotetraose, celiotriose, cellobiose), and galactooligosaccharides (galactotetraose, galactotriose) were detected in the ASDF.

2.3.2 Pigeon pea

Pigeon pea (Cajanus cajan) belongs to family Fabaceae and commonly known as Arhar or Red gram. Pigeon pea ranks sixth among pulse production in the world and it is one of the major legume (pulse) crop of the tropics and subtropics. Average world production of
pigeon pea was 3.49 million tonnes in the year 2009 (FAO statistics, 2009). India is the largest producer of pigeon pea and contributes more than 75% of world production. Pigeon pea significantly contributes to meet the dietary requirements of crude fiber, ash, fat, magnesium, manganese, and copper (Faris and Singh, 1990).

2.3.2.1 Pigeon pea milling

Before cooking or other processing operations, it is necessary to remove the fibrous seed coat (hull) of pigeon pea in order to reduce the fibre content and palatability. Pulses have 11 – 14% seed coat (husk), 2-5% germ, and remainder endosperm (Kyı et al., 1997). The hull of pigeon pea adheres tightly to the cotyledons through a gummy layer that does not allow separation of hull during milling, thus making the pulse difficult to mill. There are two approaches to remove hulls, namely wet and dry milling. Generally, the dry method of milling is used throughout the Indian subcontinent for milling of pigeon pea because the quality of splits from wet milling is poor (Kurien and Parpia, 1968). During dehulling, noticeable amounts of cotyledon material and germ are removed, which results in considerable losses (Siegal and Fawcett, 1976). In practice, traditional milling recovers only about 65-75%. Modern milling methods can recover 82-85% (Kyı et al., 1977). During milling of pigeon pea, yield was found to be only 76% against an estimated yield of 84% (Khare et al., 1966). The method of dehulling significantly affects the formation of broken and powdered particles and in case of pigeon pea it varies between 9 – 24.6% for broken and 5.5-6.1% for power (Singh et al., 1992).
2.3.2.2 Byproduct of pigeon pea

When pigeon pea seed is processed to make dhal, its recovery ranges between 65 and 75%. The remainder by-product (25-35%), known as ‘chunf’ is a good source of concentrate ration to cattle (Faris and Singh, 1990). This by-product usually consists of 3-8% broken cotyledons, 5.5 - 6.1% powder, and 10% husk. Chunf is used by dairy owners or feed mills to prepare cattle feeds. The powder and broken cotyledons are valuable sources of protein for cattle and poultry, and are sold at a higher price, when these are aspirated off husk (Kurien and Parpia, 1968).

Mueses et al. (1993) reported the possibility of using flour of pigeon pea in products prepared with rice and wheat flour. Three products namely gruel, fruit-flavored thick drink with and without 15% milk, Cookies with blends of pigeon pea flour (extrusion-cooked) and wheat. The gruel and the fruit flavored products had high acceptability based on a sensory evaluation test. Cookies with 100% pigeon pea flour were unacceptable; however, mixtures of 75% wheat flour and 25% pigeon pea flour gave cookies of attractive appearance and good taste.

Torres et al. (2006) used fermented pigeon pea ingredients in pasta products. Pigeon pea seeds were fermented in order to remove antinutritional factors and to obtain functional legume flour to be used as pasta ingredients. The fermented flour was used as an ingredient to make pasta products in a proportion of 5, 10, and 12%. The supplemented pasta products obtained had longer cooking times, higher cooking water absorptions, higher cooking loss, and higher protein loss in water than control pasta (100% semolina). From sensory evaluations, fortified pasta with 5 and 10% fermented pigeon pea flour had an acceptability score similar to control pasta. Pasta supplemented with 10% fermented pigeon pea flour presented higher levels of protein, fat, dietary fiber, mineral, vitamin E, and Trolox equivalent antioxidant
capacity than 100% semolina pasta and similar vitamins B₁ and B₂ contents. Protein efficiency ratios and true protein digestibility was improved after supplementation with 10% fermented pigeon pea flour.

**Rampersad et al. (2006)** studied the Physico-chemical and Sensory Characteristics of Flavored Snacks from Extruded Cassava/Pigeonpea Flour. The effects of pigeonpea flour (PF) addition to cassava flour (CF) on the sensory and physico-chemical quality of extrudates were investigated. Products with added PF were more yellow, had higher protein, bulk density, and water absorption index with lower expansion and water absorption index. Extrudate with 95% CF/5% PF had a suitable crisp to hard texture. All enrobed products were liked moderately to very much in overall acceptability. Chocolate extrudates were most liked (p < 0.01) for flavor and color over paprika, hickory, and cheese/onion.

### 2.3.3 Rice

*Rice* (*Oryza sativa*) is a cereal foodstuff which forms an important part of diet. India is the second largest producer of paddy. The production of rice in India was 131.27 million tonnes in the year 2009 against world production of 678.68 million tonnes (FAO statistics, 2009). Paddy contains 20-25% husk, (including about 2% trash), 6% bran, and 75% rice (2% of the rice is very small pieces, brewer’s rice, and fines).

#### 2.3.3.1 Processing and byproducts

The processing of paddy to rice involves the milling by using hullers, shellers and modern rice mills. The by-products from the hullers do not have much option to convert to value added products but to use as animal feed. The sheller and modern rice mills generate by-products, which have good option for utilization.
2.3.3.2 Byproduct of rice

The main by-products of rice mills are rice broken, husk and bran, which do not have mass acceptability in the country. Husk is being used for generating steam hard board etc. Rice bran is mainly used for oil extraction; and the oil is popularly known as rice bran oil (RBO). Broken rice are used in flour form in traditional recipes or used as animal feed. The broken were ground to rice flour, which were used by several researchers to develop extrudates as base material due higher expansion because of high starch content.

2.4 Extrusion studies

The researchers used rice, wheat, barley and other cereal flour for extrusion as a base material. The incorporation of fruits, vegetables and pulse proportions were reported.

Gillespie (1971) studied the free flowing starch substitute product for use in the food industry, which was produced from wheat flour and/or corn flour and/or rice flour and/or potato flour. The starting material was expanded in a continuous automatic pressure cooker-extruder and then dried, ground and sifted.

Buchanan (1975) discussed the development of low cost infant foods in Asia. The product is based on rice, soy flour and sugar with added vitamins and minerals. It was designed as a complete food for infants and was suitable as a snack food for young children. The ingredients were blended together then processed in a cooker-extruder, followed by a belt drier.

Singh and Smith (1997) compared the effect of the process variables temperature and moisture on the extrusion behaviour of wheat starch, whole wheat meal and oat flour. The extruder pressure, torque and specific mechanical energy and
extrudate properties of expansion, water absorption index (WAI) and water solubility index (WSI) were analyzed. Second-order polynomials were used to model the extruder response and product properties of extruded wheat starch and whole wheat meal with the process variables and wheat gram oil (WGO) level. Wheat starch and meal behaved broadly similarly but differed from oats in pressure, expansion, WSI and WAI in their response to moisture content and temperature. Addition of WGO to wheat starch increased the expansion, whereas it had little effect on the wheat meal. WGO increased the upper bound WSI and decreased the lower bound WAI for starch or meal.

Orr (1984) studied the role of twin extrusion cooking in the production of breakfast cereals. The use of twin-screw extruder cookers for manufacturing of flaked and expanded breakfast cereals was discussed. The fine maize grits or rice flour was suggested to be used instead of more expensive large grits or whole grains.

Chauhan and Bains (1988) studied the effect of some extruder variables on physicochemical properties of extruded rice-legume blends. Rice flour and flours prepared from legumes (soybean, bengal gram, green gram, black gram) were mixed (rice: legume ratio 75:25) and extruded in a Wenger X-5 extruder. Products were analyzed for physical characteristics (expansion ratio, density, water absorption index, water solubility index, fracturability, breaking strength). The best quality product was obtained by extruding a rice bengal gram mixture at a feed rate of 27.2 kg/h with an exit temperature of 95 ± 2°C.

Ruales et al. (1988) studied the nutritional quality of blended extruded foods of rice, soy and lupins. The raw materials used in the study were grits from polished rice (8-40 mesh), grits of dehulled soybeans (10-40 mesh), and debittered lupin flour. Rice : soybean (80:20 w/w) and rice: lupin (80:20 w/w) blends were adjusted to a
moisture content of 22% and extruded in a single-screw extruder. The products obtained were ground to a particle size of 60 mesh and stored in nylon-polyethylene bags at 4°C prior to analysis for moisture, protein, carbohydrate, ash, fat, starch, dietary fibre, starch availability, minerals (Zn, Fe, Ca, Mg, Cu), nutrient density, fatty acid composition and amino acid composition.

**Ryu and Lee (1988)** studied the effects of moisture content and particle size of rice flour on physical properties of the extrudate. Effects of moisture content (17-28%) and particle size (18-120 mesh) of rice flour on physical properties of extrudates were examined, using an autogenous single screw extruder. Expansion ratio increased and bulk density decreased as moisture content and particle size decreased. Cutting force decreased and air cell size became uniform as moisture content and particle size decreased. As moisture content increased, the yellowness of extrudates decreased, while the lightness increased, the apparent viscosity increased and the water solubility index decreased. The degree of dextrinization was influenced by moisture content and particle size.

**Maga and Kim (1989)** studied the co-extrusion of rice flour with dried fruits and fruit juice concentrates. Dried fruits paste (prunes, raisins, figs and cranberries) at levels of 0, 10 and 20% and non-reconstituted juice concentrates (orange, pineapple, cranberry and grape) at levels of 0, 3.5 and 7.0% were blended with rice flour and water. The blends obtained were extruded in a laboratory Brabender single-screw extruder. Extruder torque and various extrudate properties (yield, density, expansion ratio, color, pH and overall sensory acceptability) were observed. Results indicated that the extrudates containing dried fruits or juice concentrates compared favorably to those produced exclusively from rice. Incorporation of the fruits and concentrates produced a significant reduction in extruder torque.
Kim et al. (1989) studied the properties of extruded dried distiller grains and flour blends. 0, 20, 50 and 100% of corn, wheat, rye, barley, sorghum and oat-derived distillers dried grains (DDG) were blended with corn, potato, rice and wheat flours, at a total moisture content of 22%, and extruded in a Brabender laboratory single screw extruder at barrel temp. of 170 or 210°C. A 3:1 compression ratio screw operating at 100 rev/min and a 3.175 mm die were used for all runs. In general, extruder torque requirement decreased with increasing levels of DDG, while product density increased. Extrudate longitudinal expansion index increased with increasing DDG. Yield and radial expansion either increased or decreased, depending on DDG type and amount.

Visessurakarn et al. (1991) reported the use of broken rice for breakfast cereals. Processing conditions for production of a broken rice-based breakfast cereal were: extruder temperature of 180°C; 2mm die; and initial moisture content of raw mix, 13%. Proportions of ingredients giving the highest acceptability score were: flour mix (comprising equal ratios of broken rice and maize flours) 83.8%, sugar 15%, salt 1% and cocoa powder 0.2%. This formulation contained per 100 g 3.63 g protein; 2.2 g fat; 2 g ash; 0.02, 0.02 and 0.8 mg vitamins B1, B2 and niacin, respectively; 3.0 mg Fe and 5.6% moisture, and gave an acceptability score of 6.90 ± 0.79 on a 9-point hedonic test scale.

Abdel et al. (1992) studied the effect of extrusion cooking on the physical and functional properties of wheat, rice and fababean blends. Blends of wheat flour/faba bean meal (W/F) and rice flour/faba bean protein concentrate (R/FP) were extruded on a laboratory Brabender extruder in order to investigate effects of feed moisture, barrel temperature and screw speed on physical, functional and structural properties of the resulting extrudates. Increasing feed moisture level reduced the torque reading in
the barrel. Higher feed moisture level reduced expansion, density, product appearance and water solubility index of W/F extrudates. Higher temperature affected the physical properties of W/F in a similar way; R/FP extrudates showed no effects and enhanced properties, when processed at higher moisture and temperature levels, respectively.

Ming et al. (1993) studied the factors affecting starch degradation of rice extruded by a twin-screw extruder. Effects of processing variables (feed moisture content, 11-19%; feed rate, 332-576 g/min; barrel temperature and screw speed and 110-210 rpm), flour particle size, rice varieties, and additives (monoglyceride, salt, sucrose and soy protein isolate) on starch degradation in extruded rice flour were studied. Degree of starch degradation was determined using water solubility index (WSI), water soluble carbohydrate (WSC) and total dextrins (TD). WSI, WSC and TD increased with increasing screw speed and decreasing feed moisture content. Feed rate significantly affected WSC, when the feed moisture content was greater than 15% and the screw speed greater than 160 rpm.

Bhattacharya and Prakash (1994) applied response surface methodology to design the experimental combination of blends of rice and chick pea flours. Blends of rice and chick pea flours, containing 20% moisture, were extruded through a single-screw extruder. The extrusion process variables were: (i) feed ratio (ratio of the solids of rice and chick pea flour = 100:0, 90:10 and 80:20), and (ii) temperature of die (100, 125 and 150°C). The torque during extrusion was measured, as well as product characteristics such as expansion ratio, bulk density and shear strength. Response surfaces of these parameters were generated using a second degree polynomial. Incorporation of chick pea into rice flour decreased torque and product expansion, but
increased bulk density and shear strength. The temperature of the die had a linear effect on these parameters.

**Lee and Han (1997)** optimized the extrusion process of rice, soy protein and fish mixture by response surface methodology. Effects of raw material composition, feed moisture and die temperature on chemical, physical and sensory properties of extrudates produced by a single-screw extruder from mixtures of rice flour, isolated soy protein and file fish were evaluated. Nitrogen solubility index, integrity index, rehydration ratio, density, lightness and external appearance of extrudates were measured as indices of the changes of physicochemical properties of extrudates. Increased amounts of rice flour (up to 30%) in feed mixtures resulted in increased rehydration ratio, but decreased density. Extrudate prepared at die temperature greater than or equal to 130°C gave the highest sensory scores.

**Ascheri et al. (1998)** prepared the snacks from mixtures of rice and sweet potato flours by thermoplastic extrusion. Response surface methodology was used to determine effects of independent processing variables (feed moisture content, extruder temperature, mix formulation) on paste viscosity during extrusion, hardness, water solubility index, water absorption index and sensory properties (flavour, hardness and crunchiness) of the snacks. Initial paste viscosity (Brabender units) at 25°C and final viscosity at 50°C were highest in the rice snack mix and lowest in sweet potato alone; viscosity of the blend was intermediate. Hardness was significantly affected by formulation and moisture flour content; hardness was lower in rice than in sweet potato snacks. Water absorption and water solubility indices were affected by both formulation and moisture content; formulation had a greater influence than moisture content. Sensory scores for flavour, hardness and crunchiness were all significantly higher (P < 0.05) for the rice snack than for the snacks with 50 and 100% sweet potato.
Overall, it was concluded that inclusion of sweet potato flour in extruded snacks made from rice flour had an adverse effect on their functional and sensory properties.

Yeh and Jaw (1999) studied the effects of feed rate and screw speed on operating characteristics and extrudate properties during single-screw extrusion cooking of rice flour. Rice flour was used to examine effects of feed rate and screw speed on the specific energy input during single-screw extrusion cooking. Torque, raised by decreasing screw speed or increasing feed rate, was found to be a power law function of the ratio of feed rate to screw speed (Fr/Ss) with $r^2 > 0.94$. Specific mechanical energy (SME) calculated from torque also was a power law function of Fr/Ss with $r^2 > 0.84$ and negative power law indices. The intrinsic viscosity correlated well with the degree of gelatinization, WAI, and cooking loss, and appeared to be a good index of the extrudate properties.

Banerjee and Chakraborty (2000) analyzed the shear and thermal effect on extrusion energy, pressure requirement and viscosity of dough. The effect of moisture and shear rate on rheological properties of the rice flour was also studied. Moisture content 15, 21, 27% (wet basis), extruder barrel temperature (120, 150, 180°C) and extruder screw speeds (100, 150, 200) rpm were considered as input variables. Regression analysis showed that moisture content and temperature were negatively correlated with development pressure and specific power requirement. Screw speed was observed to be directly proportional to pressure and power requirement. Viscosity of the extruded dough increased with shear rate.

Guha et al. (2003) applied the Plackett-Burman experimental design to screen 10 extruder and extrusion variables during extrusion of rice flour, and the effect of these variables on the system parameters and target product parameters
without using any die during expression were determined quantitatively. Variables studied included: extruder hardware variables such as mixing disk (MD) and reverse pitch screw element (RPSE); effected feed variables such as moisture, sugar, salt and amylose content of the feed and rice flour particle size; and extrusion operating variables such as barrel temp., feed rate and screw speed. System parameters determined were torque, specific mechanical energy and residence time, while target product parameters included bulk density, water solubility index and paste viscosity. Results showed that screw configuration, particularly the presence of MD and RPSE, effected extrusion and extrudate properties. Marked effects were obtained for amylose and moisture content, feed rate, screw speed and barrel temperature. A combination of high barrel temperature in the presence of RPSE and MD using a low amylose content in feed was found to be desirable to achieve high water solubility index in the extruded product. It was concluded that experimental design based on the Plackett-Burman theory can be applied efficiently to screen a large number of extrusion variables including discrete variables.

Mouquet et al. (2003) tested the ability of a 'very low-cost extruder' to produce instant infant flours at a small scale in Vietnam. Factors influencing the performance of traditional low-cost extruders used in Vietnam for the preparation of infant flours were investigated. Premixes containing rice (49.9-52.4%), soybeans (0-27.1%) and sesame seeds (0-5.7%) were extruded. Extrusion of rice-sesame blends with low lipid and water contents (less than 6% dry basis and 10% wet basis, respectively) led to total starch gelatinization, which was required. Addition of soybean flour to extruded rice-sesame blends, together with milk powder, sugar, minerals and vitamins, resulted in a product with the appropriate macro and micronutrient balance.
Young and Schwarz (2004) studied the physical and cooking properties of restructured grain extruded from selected cereal and legume flours. The cooking and physical properties of restructured grain (RGR) extruded from various cereal flours and legume meals were also investigated. RGR products were prepared, using a twin screw extruder, from brown rice, pearl barley, whole wheat, sorghum, foxtail millet, soybeans and adzuki beans. In comparison to milled rice, RGR had lower L and a values; upon cooking, brightness increased slightly, whereas yellowness and redness decreased. Hardness, gumminess and chewiness were lower in cooked RGR than in milled rice, but springiness and cohesiveness were higher. Changes in hardness of cooked RGR occurred slowly at 25°C and rapidly at 4°C.

Ding et al. (2005) studied the effect of extrusion conditions on the physicochemical properties and sensory characteristics of rice-based expanded snacks. The effect of extrusion conditions, including feed rate (20–32%), feed moisture content (14–22%), screw speed (180–320 rpm), and barrel temperature (100–140°C) on the physicochemical properties (density, expansion, water absorption index (WAI), and water solubility index (WSI) and sensory characteristics (hardness and crispness) of expanded rice snack. Increasing feed rate resulted higher expansion, lower WSI, and higher hardness, whereas increasing feed moisture content produced extrudates with a higher density, lower expansion, higher WAI, lower WSI, higher hardness and lower crispness. Higher barrel temperature increased the extrudate expansion but reduced density, increased the WSI and crispness of extrudate. Screw speed had no significant effect on the physicochemical properties and sensory characteristics of the extrudate.

Ding et al. (2006) investigated the effect of extrusion conditions, including feed rate (20–32 kg/h), feed moisture content (14–22%), screw speed (180–320 rpm),
and barrel temperature (100–140°C) on the functional properties (density, expansion, water absorption index (WAI), and water solubility index (WSI)) and physical properties (density, expansion and textural characteristics) of an expanded wheat snack. Feed rate influenced hardness increase and decrease in energy to puncture the extrudates. Moisture content resulted higher density, lower expansion, lower WAI, higher WSI, higher hardness and lower puncture energy. But screw speed caused slight reduction of density and hardness of wheat extrudate when the values were increased. Higher barrel temperature reduced density, WAI, and hardness, but increased the WSI and puncture energy of extrudate.

Iabnoglu et al. (2006) investigated the effect of screw speed (220–340 rpm) and feed rate (22.0–26.0 kg/h, db) on the firmness, expansion ratio, colour and sensory properties of a nutritionally balanced gluten-free extruded snack. Regression equations describing the effect of each variable on the responses were obtained. Results indicated that feed rate and screw speed both had an effect on the firmness of the product at 95% confidence interval (CI). The interaction between the two factors was also found to be significant at 95% CI. The effect of screw speed was significant whereas the quadratic effect of feed rate was found significant on the lateral expansion (95% CI). Lateral expansion increased as screw speed increased. The results indicated that changes in the extrusion variables did not affect the flavour and overall acceptability of the final product at 95% CI for the feed rate and screw speed ranges studied.

Pansawat et al. (2008) extruded a formulation containing rice flour, fish powder, menhaden oil and vitamin E at a feed rate of 10 kg/h using a co-rotating twin-screw extruder. Primary extrusion (independent) variables were temperature (125–145°C), screw speed (150–300 rpm) and feed moisture (19–23 g/100 g db).
Response surface methodology (RSM) was used to study the effects of extrusion conditions on secondary extrusion variables (product temperature, pressure at the die, motor torque, specific mechanical energy input and mean residence time) and physical properties of the extrudates. Second-order polynomial models were computed and used to generate contour plots. Feed moisture and screw speed decreased pressure at the die, whereas increased screw speed increased product temperature at the die but increased feed moisture lowered that. Higher barrel temperature, feed moisture and screw speed decreased motor torque and screw speed increased specific mechanical energy, while increased feed moisture reduced that. Longer mean residence times were observed at lower screw speeds. Product density increased as feed moisture increased, but decreased with screw speed. Increased feed moisture decreased radial expansion.

**Stojceska et al. (2008)** incorporated cauliflower by-products as a new source of dietary fibre, antioxidants and proteins in cereal based ready-to-eat expanded snacks. Dried and milled cauliflower at levels of 5–20% was added to the formulation mix. The results obtained from the analysis of the extrudates were discussed in terms of the effect of cauliflower co-products on nutritional and textural characteristics, and the effects of processing conditions. The samples were processed in a twin-screw extruder with a combination of parameters including: solid feed rate of 20–25 kg/h, water feed adjusted to 9–11%, screw speed of 250–350 rpm and process temperatures 80–120 °C. Pressure, torque and material temperature during extrusion were recorded. It was found that addition of cauliflower significantly increased the dietary fibre ($r^2 = 0.9***$) and levels of proteins. Extrusion cooking significantly ($P < 0.0001$) increased the level of phenolic compounds and antioxidants but significantly ($P < 0.001$) decreased protein in vitro digestibility and fibre content in the extruded products. The
expansion indices, total cell area of the products, wall thickness showed negative correlation to the level of cauliflower. Sensory test panel indicated that cauliflower could be incorporated into ready-to-eat expanded products up to the level of 10%.

**Yagci and Gogus (2008)** used response surface methodology to investigate the effects of extrusion conditions including moisture content (12–18%), temperature (150–175°C), screw speed (200–280 rpm), and change in feed composition, durum clear flour (8–20%), partially defatted hazelnut flour (PDHF) (5–15%) and fruit waste (3–7%) contents on the physical and functional characteristics of the extruded snack food based on rice grit in combination with fruit waste, durum clear flour and PDHF. Response variables were bulk density, porosity, water absorption and water solubility indices and sensory properties of the extruded snacks. The product responses were most affected by changes in PDHF content and to a lesser extent by fruit waste content. Increasing PDHF content caused increase in bulk density and water solubility index, but decrease in porosity and water absorption index of the extruded snacks. Changing process conditions affected the physical and functional properties of produced snacks. The sensory evaluation suggested the production of acceptable extruded snacks from the extrusion of PDHF, fruit waste and durum clear flour in combination with rice grit.

**Altan et al. (2008)** blended barley flour and grape pomace and extruded in a co-rotating twin-screw extruder. Response surface methodology using a central composite design was used to evaluate the effects of independent variables, namely die temperature (140–160°C), screw speed (150–200 rpm) and pomace level (2–10%, db) on product responses (expansion, bulk density, texture and color). Sensory analysis was carried out for selected extrudates for appearance (color, porosity), taste (bran flavor, bitterness and sweetness), off-odor, texture (hardness, crispness and
brittleness) and overall acceptability. Multiple regression equations were obtained to describe the effects of each variable on product responses. The product responses were most affected by changes in temperature, pomace level and to a lesser extent by screw speed. The results suggested the production of acceptable barley flour and grape pomace based extruded snack food.

**Altan et al. (2008a)** also blended barley flour and tomato pomace and processed in a co-rotating twin-screw extruder. Experimental design with die temperature (140–160°C), screw speed (150–200 rpm) and tomato pomace level (2–10%) as independent variables produced 20 different combinations to investigate the effect of these variables on system parameters (SME, die melt temperature and die pressure) and product responses (expansion, bulk density, water absorption and solubility indices, texture and color). Extrudate from five experiments within 20 samples was selected for sensory evaluation in terms of color, texture, taste, off odor and overall acceptability. Regression equations describing the effect of each variable on the system parameters and product responses were obtained. The system parameters and product responses significantly affected by changes in temperature, pomace level and to a lesser extent by screw speed. The results indicated that tomato pomace can be extruded with barley flour into an acceptable and nutritional snack.

**Chakraborty and Banerjee (2009)** implemented response surface methodology to study the effect of feed moisture and metering zone temperature on physical properties of green gram extrudate. Temperature and moisture had significant effect on expansion ratio, which decreased with increasing moisture content. The viscosity of rice green gram dough decreased resulting lesser power consumption due to increase in screw speed.
Shirani and Ganesharanee (2009) included fenugreek polysaccharide for the physical and sensory quality characteristics of chickpea rice based extruded products. Based on preliminary evaluation with different proportions of chick pea and rice, a blend of 70:30 chickpea and rice was chosen as the control for further studies. The control blend, replaced with fenugreek flour at 2%, 5% and 10%, or fenugreek polysaccharide at 5%, 10%, 15% and 20%, was extruded at the optimum processing conditions. The extruded products were evaluated for their physical (moisture retention, expansion, hardness, water solubility index and water absorption index), sensory (flavor, texture, color and overall acceptability) characteristics to evaluate their suitability as extruded snack products. Due to the distinct bitter taste, inclusion of fenugreek flour was not acceptable at levels more than 2% in extruded chickpea based products. The incorporation of fenugreek, in the form of debittered polysaccharide was suggested up to a level of 15% in a chickpea rice blend to develop snack products of acceptable physical and sensory properties.

Mesa et al. (2009) blended the soy protein supplementation to increase the nutritional value of starch-based expanded snacks. A systematic study was conducted to serve as baseline for optimizing the addition of soy protein concentrate (SPC). Physical and microstructural properties of native corn starch–soy protein concentrate (CS–SPC) extrudates were investigated in relation to the macromolecular changes in starch during extrusion. The effects of extruder screw speed (230 and 330 rpm) and SPC concentration (0%, 5%, 10%, 15%, 20%) on the above mentioned parameters were determined. Increasing screw speed resulted in higher specific mechanical energy (SME) and expansion, and lower mechanical strength. On the other hand, addition of 5–20% SPC led to lower SME and expansion, and higher mechanical strength. X-ray micrographs showed smaller yet more cells, and cell wall thickening.
with SPC addition. Water absorption index increased and water solubility index decreased with increase in screw speed and SPC level. Increasing screw speed resulted in a slight shift towards smaller molecular weight fractions of starch, as determined by gel permeation chromatography.

2.5 Application of response surface methodology for process optimization

The response surface methodology (RSM) has proved a very useful tool in product design. In RSM, tests are performed using different combinations of levels of the experiments according to the predetermined design, and an appropriate data is fitted by method of least square. Three dimensional plot provide a useful visual aid for checking the adequacy of the model and for examining the response surface and the location of the optimum. RSM is reported to be an efficient tool for optimizing a process, when the independent variables have the joint effect on the responses. Chakraborty and Banerjee (2009) implemented response surface methodology to study the effect of feed moisture and metering zone temperature on physical properties of green gram extrudate. Altan et al. (2008) also blended barley flour and tomato pomace and processed in a co-rotating twin-screw extruder. Experimental design with die temperature, screw speed and tomato pomace level as independent variables produced 20 different combinations that were studied using response surface methodology to investigate the effect of these variables on system parameters. Yagci and Gogus (2008) used response surface methodology to investigate the effects of extrusion conditions including moisture content, temperature, screw speed, and change in feed composition, durum clear flour, partially defatted hazelnut flour and fruit waste contents on the physical and functional characteristics of the extruded snack. Pansawat et al. (2008) also used response surface methodology to study the
effects of extrusion conditions on secondary extrusion variables and physical properties of the extrudates.