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Desarrollo de una línea de producción piloto de Flash Explosión para la obtención de puré de gulupa (*Passiflora edulis* Sims) y uchuva (*Physallis peruviana* L.)

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Facultad Ciencias Agrarias

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Medellín, Colombia

2022

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RESUMEN

Los frutos de uchuva (*Physallis peruviana* L) y gulupa (*Passiflora edulis* Sims) son considerados como frutos tropicales, muy apreciados por el consumidor por su aroma intenso y sabor entre dulce y dulce-amargo. Estos frutos presentan un alto interés comercial, debido a su composición y potencial efecto benéfico sobre la salud.

El objetivo fue, estandarizar las condiciones operativas de una línea de proceso de flash explosión para la obtención de purés de gulupa y uchuva. Se evaluó el impacto del tiempo de calentamiento y aplicación de presión de vacío sobre las propiedades fisicoquímicas, reológicas, sensoriales y microbiológicas y vida útil de los purés de uchuva y gulupa. En este contexto, la investigación se planteó en dos etapas:

En la 1ª etapa se planteó la evaluación del proceso de Flash Explosión sobre los atributos de calidad fisicoquímico, microbiológico y sensorial. Los purés de uchuva y gulupa se obtuvieron utilizando una línea piloto Flash Explosión (FE), compuesta por una cámara cilíndrica de acero inoxidable unida por una válvula neumática que se acopla a una cámara de expansión de vacío donde se instala una despulpadora giratoria. El equipo se conecta a dos tanques asépticos para la recuperación de productos y coproductos. Los procesos FE se llevaron a cabo con 4 repeticiones. El análisis de datos se realizó mediante el software estadístico XLSTAT 2022.1.1 (Addinsoft) teniendo en cuenta las variables independientes: para el diseño experimental que se realizó para gulupa así: tiempos de calentamiento 80, 95 y 110s, proceso con presión de vacío 5 kPa y proceso sin presión de vacío (presión atmosférica de aproximadamente 80 kPa). Las variables dependientes evaluadas fueron: Mohos y levaduras, aerobios mesófilos, coliformes fecales, coliformes totales; rendimiento (Y) %, pH, L*, a*, b*, SS ($g.L^{-1}$, β-carotenos (mg/100 g PF), WAIR (g/100 g AIR), AIR (g/100 g PF), SIS (g/100 g PF), índice de consistencia (K), comportamiento de flujo (n), Viscosidad a σ: 50 s-1 (mPa s), cianidina 3 glucósido (mg/100g PF). Se definió un mejor tratamiento para los purés de gulupa con las variables de proceso T: 90 ºC (110s) y presión de vacío a 5 kPa, con atributos de calidad: mohos y levaduras:0; coliformes fecales y totales: 0; aerobios mesófilos: 0; % rendimiento (Y) %: 47.29±5.95; pH: 3.15±0.04; acidez: 1.69±0.11; SS (g.L-1): 10.43±1.34; L*:23.82±2.24 ; a*:30.63±5.01; b*:21.61±5.66; WAIR (g/100g AIR); 14.48±1.61; AIR (g/100g PF): 5.49±0.08; SIS (g/100g PF):100±0.00; índice de consistencia (K): 10.69±0.11; comportamiento de flujo (n): 0.58±0.00; Viscosidad a σ: 50 s-1 (mPa•s): 2078.19±6.67; β-carotenos (mg/100g PF): 2.58±0.25; cianidina 3 glucósido (mg/100g PF): 20,0±5.01.

Las variables independientes evaluadas para uchuva fueron: tiempos de calentamiento 30, 40 y 50s, proceso con presión de vacío 5 kPa y proceso sin presión de vacío (presión atmosférica de aproximadamente 80 kPa). Las variables dependientes evaluadas fueron: Mohos y levaduras, aerobios mesófilos, coliformes fecales, coliformes totales; rendimiento (Y) %, pH, L*, a*, b*, diferencias de color totales (ΔE*), índice de pardeamiento (BI), SS (g.L-1), ácido ascórbico (mg/100 g PF), β-carotenos (mg/100 g PF), se realizó simulación de transferencia de calor utilizando el programa COMSOL. Se definió un mejor tratamiento para los purés de uchuva con las variables de proceso: T:50 ºC (40s) con presión de vacío a 5 kPa, con atributos de calidad: mohos y levaduras: 0; coliformes fecales y totales: 0; aerobios mesófilos: 0; rendimiento(Y) %: 68,25±0,07; pH: 3,86±0,07; L*: 52,24±0,44; a*: 24,42±0,24; b*:65,35±1,31; SS (g.L-1): 13,10±1,22; Ácido ascórbico (mg/100g PF): 39,69±3,62); acidez:1.45±0.10; β-carotenos(mg/100gPF):2,89±0,02; BI:31.57±0.43b; ΔE*:4.93±0.51.

En la segunda etapa se realizó la evaluación de la vida útil, a través de estudios de almacenamiento en tiempo real, considerando las variables independientes: temperatura (4 y 20 ºC) y tiempo (90 y 16 días respectivamente), para gulupa y uchuva, las variables dependientes fueron: mohos y levaduras, aerobios mesófilos, coliformes fecales y totales color (L, a*, b) y biocompuestos: uchuva (ácido ascórbico y β- caroteno) y gulupa (β-caroteno y antocianinas). Las variables dependientes se determinaron para 20 °C durante16 días y con tiempos de control cada 8 días; mientras que, para 4°C se determinaron durante 90 días y tiempos de control cada 30 días hasta el día 60 y después cada 15 días hasta el día 90. Para gulupa se realizó una evaluación general de la calidad utilizando una escala hedónica de 9 puntos. La vida útil de los purés de gulupa y de uchuva en función de la calidad nutricional, sensorial y microbiológica, se extendió hasta 90 días a temperatura de refrigeración. Estos resultados demuestran que el proceso FE, permite obtener purés de gulupa y de uchuva de alta calidad y con una vida útil promedio de tres meses a temperatura de refrigeración comercial.

Palabras clave: *Physallis peruviana* L., *Passiflora edulis* Sims, Flash explosion, tecnología innovadora, expansión instantánea bajo vacío, calidad, vida útil

Development of a pilot production line for Flash Explosion for the extraction of purée from passion fruit (*Passiflora edulis* Sims) and gooseberry (*Physalis peruviana* L.)

Abstract

Cape gooseberry (*Physallis peruviana* L) and gulupa (*Passiflora edulis* Sims) fruits are considered tropical fruits, highly appreciated by consumers for their intense aroma and taste between sweet and sweet-bitter. These fruits have a high commercial interest, due to their composition and potential beneficial effect on health.

The objective was to standardize the operating conditions of a flash explosion process line to obtain gulupa and cape gooseberry purees. The impact of heating time and application of vacuum pressure on the physicochemical, rheological, sensory and microbiological properties and shelf life of cape gooseberry and gulupa purees was evaluated. In this context, the research was planned in two stages:

In the 1 stage, the evaluation of the Flash Explosion process was proposed on the physicochemical, microbiological and sensory quality attributes. Cape gooseberry and gulupa purées were obtained using a Flash Explosion (FE) pilot line, composed of a cylindrical stainless steel chamber connected by a pneumatic valve that is coupled to a vacuum expansion chamber where a rotating pulper is installed. The equipment is connected to two aseptic tanks for the recovery of products and co-products. The FE processes were carried out with 4 repetitions. The data analysis was carried out using the statistical software XLSTAT 2022.1.1 (Addinsoft) considering the independent variables: for the experimental design of gulupa as follows: heating times 80, 95 and 110s, process with vacuum pressure 5 kPa and process without vacuum pressure (atmospheric pressure of about 80 kPa). The dependent variables evaluated were: molds and yeasts, mesophilic aerobes, fecal coliforms, total coliforms; yield (Y) %, pH, L*, a*, b*, SS (g.L-1, β-carotenes (mg/100 g FW), WAIR (g/100 g AIR), AIR (g/100 g FW), SIS (g/100 g FW), consistency index (K), flow behavior (n), Viscosity at σ: 50 s-1 (mPa s), cyanidin 3 glucoside (mg/100g FW). A better treatment was defined for the gulupa purées with the process variables: T: 90 ºC (110s) with vacuum pressure at 5 kPa, with quality attributes: molds and yeasts: 0; fecal and total coliforms: 0; mesophilic aerobes: 0; % yield (Y)%: 47.29±5.95, pH: 3.15±0.04; acidity: 1.69±0.11; SS (g.L-1): 10.43±1.34; L*:23.82±2.24 ;

a*:30.63±5.01; b*:21.61±5.66; WAIR (g/100g AIR); 14.48±1.61; AIR (g/100g FW): 5.49±0.08; SIS (g/100g FW):100±0.00; consistency index (K): 10.69±0.11; flow behavior (n): 0.58±0.00; Viscosity at σ: 50 s-1 (mPa•s): 2078.19±6.67; β-carotene (mg/100g FW): 2.58±0.25; cyanidin 3 glucoside (mg/100g FW): 20.0±5.01.

The independent variables evaluated for cape gooseberry were: heating times 30, 40 and 50s, process with vacuum pressure 5 kPa and process without vacuum pressure (atmospheric pressure of approximately 80 kPa). The dependent variables evaluated were: molds and yeasts, mesophilic aerobes, fecal coliforms, total coliforms; yield (Y) %, pH, L*, a*, b*, total color differences (ΔE*), browning index (BI), SS (g.L-1), ascorbic acid (mg/100 g FW), β-carotene (mg/100 g FW), heat transfer simulation was performed using the COMSOL program. A better treatment was defined for cape gooseberry purees with the process variables: T: 50 ºC (40s) with vacuum pressure at 5 kPa, with quality attributes: molds and yeasts: 0; fecal and total coliforms: 0; mesophilic aerobes: 0; yield(Y)%: 68.25±0.07; pH: 3.86±0.07; L*: 52.24±0.44; a*: 24.42±0.24; b*:65.35±1.31; SS (g.L-1): 13.10±1.22; Ascorbic acid (mg/100g FW): 39.69±3.62); acidity:1.45±0.10; β-carotene(mg/100gFW):2.89±0.02; BI:31.57±0.43b; ΔE*:4.93±0.51.

In the second stage, the evaluation of the useful life was carried out, through real-time storage studies, considering the independent variables: temperature (4 and 20 ºC) and time (90 and 16 days, respectively), for gulupa and cape gooseberry, the dependent variables were: molds and yeasts, mesophilic aerobes, fecal coliforms and total color (L, a*, b) and bio compounds: cape gooseberry (ascorbic acid and β-carotene) and gulupa (β-carotene and anthocyanins). The dependent variables were determined for 20 °C for 16 days and with control times every 8 days; while, for 4°C, they were determined for 90 days and control times every 30 days until day 60 and then every 15 days until day 90. For gulupa, a general quality evaluation was carried out using a 9-point hedonic scale. The shelf life of the gulupa and cape gooseberry purées, depending on the nutritional, sensory and microbiological quality, was extended up to 90 days at refrigeration temperature. These results demonstrate that the FE process allows obtaining high-quality gulupa and cape gooseberry purées with an average shelf life of three months at commercial refrigeration temperature.

Keywords: *Physallis peruviana* L., *Passiflora edulis* Sims, Flash explosion, innovative technology, instant expansion under vacuum, quality, shelf life.

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INTRODUCCIÓN

Interés de la investigación.

Durante los últimos años, el aumento del consumo de frutas y verduras ha ido crecimiento. Los consumidores marcan con sus exigencias, la tendencia a complementar su nutrición con productos saludables y listos para consumir; que aporten beneficios adicionales a su salud. Colombia es uno de los países con mayor potencial en la producción de frutas; en este ámbito, se debe aprovechar las frutas exóticas con alto valor nutricional y de consumo a nivel mundial, para generar capacidades, infraestructura, bienes y servicios que permitan la disponibilidad, el acceso, la calidad e inocuidad, lo cual promueve una alimentación saludable, generación de valor y una mayor competitividad de las agrocadenas (Zuluaga, 2015).

La uchuva y la gulupa son frutas tropicales exóticas muy apetecida por el consumidor debido a sus cantidades apreciables de carbohidratos, minerales, vitaminas, fibras esenciales y antioxidantes (Ordóñez-Santos et al., 2017). “Las frutas exóticas se caracterizan por su apariencia y sabor único y peculiar, muy diferente al de las tradicionales. Debido al sabor acidulado, la mayoría de ellas son utilizadas para calmar la sed rápidamente. Además, cuentan con propiedades medicinales y terapéuticas” (Zuluaga, 2015). Según cifras del instituto Agropecuario Colombiano, en 2021 el país exportó 9.813 toneladas de gulupa y el valor de las exportaciones alcanzó los 42 millones de dólares; las exportaciones de uchuva en el 2021 fueron de 7.872 toneladas con un valor de 37.820.445 millones de dólares (Min Agricultura 2022), siendo los principales destinos de exportación Países Bajos, Estados Unidos y Reino Unido (Procolombia, 2021).

Colombia es un país rico en producción frutícola, sin embargo, su mayor consumo es en estado fresco y su uso como materia prima en los sistemas productivos corresponde principalmente a pequeños empresarios. Normalmente los productores o agricultores y comercializadores llevan el fruto en estado fresco a los mercados locales; además, se ha evidenciado que existe poca experiencia en la tecnificación y desarrollo de productos que generen valor agregado (DNP, 2014). La agregación de valor a productos de origen agropecuario está relacionada con el interés en que los productores primarios y los territorios incrementen sus ingresos y su participación en la definición de los precios finales de los productos (Lasprilla, 2011); en este sentido, es necesario que agricultores,

científicos, consumidores, empresarios, procesadores de alimentos, nutricionistas, distribuidores y legisladores trabajen juntos para atender las nuevas necesidades de los consumidores e impulsar el crecimiento económico del sector agrario.

Frente a la situación se hace necesaria la inserción de nuevas técnicas o tecnologías mejoradas en los sistemas productivos de pequeñas y medianas agroempresas que permitan incrementar la productividad y competitividad con el desarrollo de nuevos productos que estimulen la sostenibilidad de las agrocadenas de frutas. Dada la importancia de la implementación de nuevas tecnologías para la transformación y desarrollo de nuevos productos que generen valor agregado, el propósito de este trabajo de investigación, es generar un avance significativo en la agroindustria de gulupa y uchuva, mediante la aplicación de procesos estandarizados en una línea de proceso de Flash Explosión para la obtención de purés, con el objetivo de obtener un control más estricto del proceso y de esta manera lograr una calidad del producto que permita el desarrollo de purés de calidad, prolongando su vida útil y garantizando su contenido nutricional a través del tiempo de almacenamiento, productos con valor agregado que representen nuevas alternativas de innovación.

La tecnología Flash Explosión representa una alternativa para la obtención de purés de gulupa y uchuva de calidad. Entre las ventajas que presenta esta tecnología se encuentran: facilita la extracción de compuestos bioactivos del fruto completo (incluyendo cáscaras y semillas), inactivación enzimática, recuperación de compuestos volátiles aromáticos, reducción de operaciones de proceso, reducción de procesos oxidativos (proceso al vacío), cortos tiempos de operación, es ampliamente usado a nivel industrial en gran escala y puede operarse en continuo (Paranjpe et al., 2012). Consiste en someter bajo vacío a una materia prima previamente calentada, produciéndose una vaporización instantánea de una parte del agua contenida en los tejidos vegetales del fruto acompañado de una posible destrucción de la estructura y un enfriamiento inmediato, que conlleva a una aceleración de los fenómenos de difusión o de maceración de sus componentes (Ortiz Valero, 2013).

1. MARCO TEÓRICO

1.1 Generalidades de la de la gulupa.

Passiflora edulis Sims*,* es una fruta exótica originaria del sur de Brasil, la cual fue ampliamente distribuida durante el siglo 19 a otros países de América del Sur, el Caribe, Asia, África, India y Australia (Joaquín et al., 2022). El fruto de gulupa es rico en agua (≅ 90%); además, presenta un alto contenido de vitamina A y ácido ascórbico, lo que indica que el fruto es rico en compuestos antioxidantes que ayudan a incrementar el bienestar del consumidor (Tabla 1-1). El fruto tiene forma redonda a levemente oblonga. Su cáscara (pericarpo) es lisa y firme en el exterior, presentando colores desde verdes claro hasta púrpura oscuro; mientras que, el interior es blanco, blando y de textura medulosa o porosa. El interior del fruto (figura 1-1) se compone de semillas negras y ovaladas, recubiertas con arilo de color amarillo a naranja, que constituye la pulpa del fruto (Orjuela Baquero et al., 2009).

Figura 1-1. Fruto de la planta de gulupa (*Passiflora edulis* Sims)
Fuente: Elaboración propia

Tabla 1-1. Composición de la gulupa (*Passiflora edulis Sims)* (base 100 g).

Nutriente	Cantidad en 100 g
Agua	88,9 g
Proteínas	1,5 g
Grasas	0,5 g
Carbohidratos	11,0 g
Fibra	0,4 g
Cenizas	0,7 g
Calcio	9,0 mg
Fósforo (mg)	21,0 mg
Hierro (mg)	1,7 mg
Vitamina A	1730 U.I.
Calorías (mg)	49 cal.
Riboflavina (mg)	0,17 mg
Niacina (mg)	0,8 mg
Ácido ascórbico (mg)	20,0 mg
Niacina	0,8 mg

Fuente: (Orjuella Barquero et al., 2011)

1.2 Contexto económico de la gulupa.

La gulupa en Colombia es una de las frutas que ha tenido durante los últimos años mayor demanda en el mercado europeo. La exportación de gulupa superó las 8.109 toneladas y 2.013 hectáreas sembradas; mientras que, la producción se ha fortalecido en los últimos tres años, alcanzando las 24.799 toneladas en 2018. Antioquia es uno de los líderes en la cantidad de hectáreas sembradas con 13.161 toneladas (Darmawan, 2019) Agronet. (2019).

Según datos recolectados por la Asociación Hortofrutícola de Colombia, la producción de esta fruta ha aumentado 335% en los últimos 10 años. En 2008, se registró una producción anual de 7.198 toneladas; mientras que, en 2018 ascendió a 24.799 toneladas Agronet. (2018).

Este aumento de la producción también se puede ver en la evolución de hectáreas sembradas. Los reportes dados por los productores y agricultores de esta fruta exótica evidencian que, en 2018, las hectáreas sembradas llegaron a 2.013, comparado con 854 hectáreas en 2008, lo que demuestra que este cultivo representa una oportunidad económica creciente para el agricultor colombiano (Granados Perez & Lara Prado, 2018).

Otro aspecto representativo sobre el cultivo y la producción de gulupa se presentó entre 2015 y 2016, cuando se pasó de 7.816 toneladas a 15.956 Agronet. (2018).

1.3 Generalidades uchuva.

La uchuva (*Physalis peruviana* L.) pertenece a la familia de plantas *Solanaceae*, es autóctona de América del Sur, originaria de Perú. Recibe múltiples nombres alrededor del mundo; en Colombia es conocida como "*uchuva*", en los países de habla inglesa y en Turquía es llamada "*goldenberry*", en Ecuador se conoce como "*uvilla*", en Perú como "*aguaymanto*", en Venezuela como "*topotopo*" (Baena 2015;Cely et al., 2015). Esta fruta, se cultiva ampliamente en Colombia por el por la diversidad de altitudes en los que se puede desarrollar (1500-3000 msnm); sin embargo, las condiciones óptimas se encuentran entre los 1800 y 3000 msnm, temperaturas entre los 13-18°C y humedades relativas entre 70-80% (Mazorra, 2003)

Su fruto es una baya de diámetro aproximado de 1.25 a 2.50 cm, con peso promedio de 4-10 g, piel lisa, cerosa, de color amarillo anaranjado y una pulpa jugosa que contiene numerosas semillas pequeñas (Olivares et al. 2017). Se encuentra contenida en una cubierta (cáscara) con forma de vejiga y es considerada una fruta exótica (Fischer, 1995; Ramadan, 2011). Su cultivo se extiende por los Andes sudamericanos, sin embargo, se encuentra en los mercados de muchos países del mundo. Su atractivo principal son sus propiedades nutricionales y medicinales, dados sus altos niveles de compuestos fenólicos, carotenoides, vitamina E y vitamina C (Rop et al., 2012, Valdenegro et al., 2010; Vega Gálvez et al. 2014).

Las hojas de la planta tienen tamaños entre 5 y 15 cm de largo y 4 a10 cm de ancho, la planta puede alcanzar una altura hasta 1,5 m, sus flores son hermafroditas y se auto polinizan o en algunos casos la polinización ocurre con la ayuda del viento y los insectos. El fruto de la planta, la uchuva, está encerrado en un cáliz o capacho, figura 1-2, que lo protege contra insectos, aves y demás condiciones dañinas; el fruto es una baya verde en sus etapas iniciales, pero va perdiendo su coloración pasados los 40 días para tornarse de color amarillo-naranjado, su forma es redonda, pesa entre 4 y 10 g y tienen una gran cantidad de pequeñas semillas en su interior (Fischer et al., 2014).

Figura 1-2. Fruto de la planta de uchuva (*Physalis peruviana* L.)
Fuente: Elaboración propia

La uchuva es ampliamente apetecida a nivel mundial, debido a sus múltiples propiedades y beneficios para la salud, la tabla 1-2 muestra la composición nutricional de este fruto. La uchuva es una fuente importante de β-caroteno y ácido ascórbico (Olivares-Tenorio et al., 2017), debido a su alta capacidad antioxidante, se ha usado en el mundo como medicina natural para prevenir enfermedades degenerativas (Gallón et al., 2021)

Tabla 1-2. Composición de la uchuva (*Physalis peruviana* L.) (Base 100 g)

Parámetros	ICBF*	FAO**
Humedad(g)	85.00	85.90
Energía (Kcal)	60	56
Proteínas (g)	1.5	1.5
Lípidos (g)	0.50	0.50
Carbohidratos totales (g)	12.30	11.40
Cenizas (g)	0.80	0.70
Calcio (mg)	9.00	9.00
Fósforo (mg)	21.00	21.00
Hierro (mg)	1.70	0.40
Niacina (mg)	0.80	0.80
Riboflavina (mg)	0.17	0.17
Tiamina (mg)	0.01	0.01
Vitamina C (mg)	20.00	20.00
Vitamina A (µg)	520.00	520.00

Fuente: (Cortés Díaz et al., 2015).

La uchuva es consumida principalmente en estado fresco, pero también se encuentra en almíbar y/o seca, como ingrediente de ensaladas, platos cocinados, postres, mermeladas, snacks naturales y/o conservas (Ramadan, 2011).Sin embargo, por ser un fruto climatérico tiene dificultades para mantener un nivel aceptable de su calidad, debido al crecimiento de hongos, la pérdida de firmeza, el aumento del índice de madurez y la pérdida de peso durante el almacenamiento, que no debe superar el 6% (Olivares et al., 2017). Adicionalmente, se estima que entre el 10 y 15 % de la producción total del campo, está afectada por el agrietamiento superficial, lo que ha provocado importantes pérdidas económicas para los agricultores. Esta situación sugiere la elaboración de productos procesados a partir de uchuvas frescas, como jugos, pulpas, purés, que permitan el aprovechamiento de esos frutos que a pesar de presentar defectos (frutos rajados) mantienen su valor nutricional y propiedades sensoriales (Castro Sánchez et al., 2014).

1.4 Contexto económico de la uchuva

De acuerdo con las cifras del DANE y ProColombia, en 2019 la producción de la uchuva en el país se concentró en los departamentos de Boyacá y Cundinamarca, con más del 70% de la producción, seguidos por Antioquia con el 10,4%, Nariño con el 9,6% y Santander con un 4,4%. Colombia se ha convertido en uno de los exportadores más importantes de uchuva a nivel mundial, principalmente a países europeos,

considerándose la segunda fruta con mayor mercado a nivel internacional (Procolombia 2020).

La uchuva colombiana cada vez tiene un mayor impacto económico y social para el país, por su demanda en los mercados internacionales. En el 2021 se alcanzó la mayor cifra en las exportaciones de uchuva en Colombia, aumentando en un 16% en valor, al pasar de US$32.678.630 en el año 2020, a US$37.820.445, y en toneladas aumentaron un 7% al pasar de 7.363 toneladas a 7.872 toneladas en el 2021. Colombia es el mayor exportador y productor de uchuva a nivel mundial (Min Agricultura 2022).

Según los datos del DANE analizados por Procolombia, entre enero y febrero de 2022, las exportaciones de uchuva alcanzaron los US$6,5 millones de dólares. Para el mismo periodo del 2021 la cifra fue de US$5,9 millones (Semana & Agro, 2022)

Los principales destinos de exportación fueron: Países Bajos, Estados Unidos y Alemania; siendo Países Bajos el principal país de destino de la uchuva con una participación de 70,7% del total exportado en lo corrido del año, seguido de Estados Unidos con 10,9% y Alemania con 6,4% (Analdex, 2019)

1.5 Procesos tradicionales para la obtención de purés de frutas

Las frutas tienen aromas, texturas, sabores y formas diversas que representan diferentes familias, ocupan un nicho único en el sector de la agricultura mundial, ya que contribuye al 62% de la oferta de fruta fresca. Las frutas son altamente perecederas, con elevadas pérdidas poscosecha, especialmente durante el transporte para su distribución, estimándose entre un 18-28% (Md Nor & Ding, 2020). Proporcionar valor agregado a una variedad de frutas tropicales que se producen en distintos sectores del país, permite el crecimiento de la agroindustria. La elaboración de puré de frutas es una manera de conservación, la cual se basa en la aplicación de temperaturas elevadas con las cuales se llega a destruir microrganismos y a inactivar enzimas que degradan el producto. El puré de frutas es una pasta de fruta fresca cocida ligeramente al vapor y colada, con o sin conservantes añadidos, tiene una textura lisa y fina (Codex Alimentarius, 2019).No se destina generalmente al consumo directo, sino que es un producto intermedio que puede destinarse para la elaboración de productos como mermeladas, salsas, dulces y jugos. Según resolución 3929 de 2013 del ministerio de salud y protección social de Colombia las pulpas de frutas deben cumplir con requisitos microbiológicos y fisicoquímicos que garanticen la calidad e inocuidad de estos productos.

Por lo anterior se requieren tecnologías para la transformación de las frutas, que garanticen inocuidad, que no degraden en su procesamiento componentes nutricionales y que sean adaptables a las condiciones productivas de Colombia con el fin de prologar su vida útil. A nivel de gran industria esto se logra con la aplicación de diferentes tratamientos térmicos (escladado, pasteurización, etc.). Sin embargo, estos tratamientos

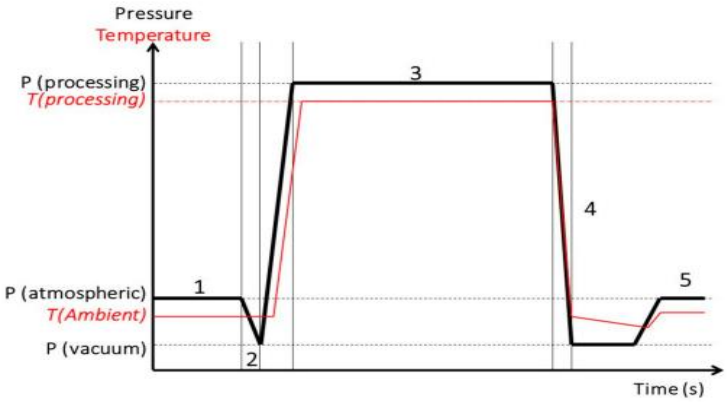
térmicos conllevan a reducción de compuestos bioactivos, de gran importancia para la calidad del producto final, por su impacto en el color y las propiedades nutricionales y funcionales de los productos (Stănciuc & Râpeanu, 2019). Existen diferentes tecnologías para procesar los alimentos para su conservación. El procesamiento térmico es el método de conservación más utilizado para prolongar la vida útil de los derivados de frutas, por el efecto letal sobre los microorganismos. Sin embargo, estos métodos tradicionales que, aunque económicos y efectivos, afectan la calidad fisicoquímica y valor nutritivo de estos alimentos (Al-Ghamdi et al., 2020).

En respuesta a estos inconvenientes y para garantizar estabilidad comercial sin afectar la calidad de los alimentos (Ordóñez-Santos et al., 2017), en los últimos años, un aumento de las investigaciones se han centrado en explorar tecnologías de procesado con enfoque en generación de productos con alto valor, que protejan o reduzcan el impacto del proceso sobre biocompuestos y a su vez, que garanticen una calidad fisicoquímica, microbiológica y sensorial, mayor vida útil y que se reduzca el consumo energético de los procesos, las temperaturas y los tiempos de los tratamientos. Por otro lado, se han realizado otras investigaciones para evaluar el efecto de otros tratamientos (mecánico, enzimático, irradiación, altas presiones hidrostáticas, pulsos eléctricos, pulsos de luz, ultrasonidos, entre otras) sobre la calidad general de los productos transformados (Magán, 2019).

1.6 Principio de la tecnología Flash explosión

La tecnología de FE se utiliza generalmente en la elaboración de vino en Europa. Este proceso inicialmente fue conocido como Termo vinificación, cuya finalidad es alterar la estructura celular calentando las uvas trituradas entre 60-80°C durante un corto tiempo, luego de enfriarlas antes de la fermentación (Enartis USA, 2015). Como resultado, se liberan instantáneamente antocianinas y taninos solubles en agua entre otros constituyentes de las células de una manera no selectiva. Este proceso es también conocido como caída de presión instantánea controlada (acrónimo en francés DIC: “Détente Instantané Contrôlée”), el cual fue inventado por Allaf y Vidal como, prácticamente, un proceso de tipo HTST (alta temperatura y corto tiempo) seguido de una caída de presión abrupta hacia el vacío (Al-Ghamdi et al., 2020). La FE es una tecnología de procesamiento térmico con alta eficiencia y bajo consumo de energía, que puede realizarse a gran escala (Zhang et al., 2017). Así, el proceso consiste en someter matrices biológicas alimentarias a tratamientos de presión de vapor saturado de 100 a 900 kPa durante unos segundos, seguidos de una caída de presión brusca y controlada a un ritmo superior a 500 kPa/s; esto lleva a un vacío final de presión absoluta de 10 a 5 kPa, significativamente inferior a 101.325 kPa (que es la presión atmosférica al nivel del mar) (ver figura 1-3). La caída de presión desencadena la vaporización instantánea del agua contenida en los frutos, seguido de una expansión y un enfriamiento inmediato de las matrices biológicas (Pech-Almeida et al., 2021). La tasa de enfriamiento puede alcanzar niveles excepcionales de 1500–2000 kW/m2 (Mazen Hamoud-Agha & Allaf, 2020), proporcionando suficiente fuerza para separar la estructura compacta de la

biomasa (Hou et al., 2014), lo que favorece una mejor y rápida extracción de todos los compuestos fenólicos (ácidos hidroxicinámicos, flavonoles, antocianinas, catequinas y proantocianidinas) (Paranjpe et al., 2012a). Además, mejora la calidad de los productos finales al reducir la degradación térmica de biocompuestos, y gracias al efecto termo-mecánico, garantiza resultados de gran relevancia de eliminación/destrucción de microorganismos tanto en forma vegetativa como las esporas.



Fuente: (Pech-Almeida et al., 2021)

Figura 1-3. Perfil de temperatura y presión involucrado en el proceso de caída de presión instantánea controlada.

La eficiencia de la inactivación microbiana con la caída de presión instantánea controlada se debe a los impactos termo mecánicos que provocan cambios irreversibles en las células de los microorganismos, como la desnaturalización de las proteínas y la rotura de la membrana celular. Dos mecanismos principales están implicados en el efecto bactericida: el tratamiento térmico elevado controlado y una liberación de presión excesiva (Mazen Hamoud-Agha & Allaf, 2020).

En el procesamiento de matrices frutales se involucra una diversidad de procesos tales como la pasterización, escaldado, despulpado, desaireacion y el pelado de los frutos, donde se evalúa en forma independiente muchos parámetros operativos a nivel industrial; mientras que, en la tecnología Flash Explosion, se realizan todas estas operaciones en un solo paso sin manipulación humana. Entre sus mayores ventajas se encuentran: aprovechamiento de fruto completo, reducción de procesos oxidativos (proceso al vacío), alteración celular, reducción de la actividad enzimática (Vargas-Ortiz et al., 2017), extracción de compuestos bioactivos y cortos tiempos de operación, lo que reduce significativamente grandes consumos de energía. Esta tecnología es un método innovador el cual se caracteriza por una mayor calidad del producto, mejor eficiencia de producción y ahorro de energía, contribuyendo a la preservación del medio ambiente, dado que mayor consumo de energía mayor emisión de gases efecto invernadero, el alto consumo de energía en los procesos de producción son una gran preocupación no solo desde el punto de vista económico sino también en términos de impacto ambiental (Mazen Hamoud-Agha & Allaf, 2020). En la **tabla 1-3**, se observan diferentes aplicaciones de altas presiones y otras tecnologías en frutas como alternativa de tratamientos térmicos convencionales.

Tabla 1-3. Aplicación de altas presiones y otras tecnologías en frutas como alternativa de tratamientos térmicos.

Tecnología	Parámetros			Ventajas	Desventajas	Referencias
	P (MPa)	T (°C)	t(min)			
Altas presiones hidrostáticas (APH)	400–600	10-35	1-6	Inactiva microorganismos, conserva características organolépticas y nutricionales vida útil prolongada.	Inversión inicial, no continuo	(Martinez Giron et al., 2021)
Pulsos Eléctricos (PEF)		55	0,4 - 0,10	Inactiva microorganismos, mantiene las cualidades organolépticas, nutricionales y operara en continuo	Limitado a ciertos líquidos, vida útil máxima 21 días.	(Vivanco et al., 2021)
Luz Ultravioleta (UV)			1-5	Inactiva microorganismos, opera en continuo, no afecta a las características organolépticas, fácil de usar.	Limitado a líquidos claros, vida útil Max de 21 días.	(Villarroel et al., 2014)
Pasteurización UHT		135 - 150	0,10	Inactivación microbiana y reducción actividad enzimática y larga vida útil.	Altera su calidad física, química y aspecto general.	(Tirado Armesto et al., 2017) (Storti, 2013)
Proceso HTST		70-75	0,15 - 0,20	Garantiza la destrucción del 100% de las bacterias patógenas y el 99% de las bacterias alterante, tiempos más largos de vida útil, no modifica la naturaleza física, química y nutritiva.	Personal cualificado, controles estrictos durante todo el proceso de producción.	(Tirado Armesto et al., 2017)
Caída de presión controlada instantánea (DIC)	0,01-0,005	40-90	0,30 - 5	Extracción de compuestos bioactivos del fruto completo, inactivación de bacterias y enzimas oxidativas, conserva propiedades fisicoquímicas y sensoriales Texturización de productos, recuperación de compuestos volátiles aromáticos.	Condiciones específicas de operación para cada matriz, control de condensados, no productos de gran tamaño.	(Mazen Hamoud-Agha & Allaf, 2020)

1.7 Aplicaciones de flash explosión

La FE, flash vacuum expansión o DIC se ha utilizado para texturización de productos vegetales ya que la expansión en la estructura de estos productos facilita la deshidratación y la extracción de componentes, siendo de gran relevancia para la industria de alimentos el aumento de la eficiencia de extracción de compuestos valiosos y el logro de calidades superiores de los productos. Ranjbar et al., (2016), utilizó el proceso de caída de presión controlada instantánea (DIC) como pretratamiento de texturización para mejorar la eficiencia de extracción de compuestos fenólicos de la cáscara de granada. Se determinó que las condiciones de operación fueron de 3 bar, 60 s y 1 ciclo. En comparación con las muestras sin texturizar, el contenido fenólico total (TPC) y la actividad antioxidante como porcentaje de inhibición aumentaron de 38,77 a 46,02 mg AG/g base seca y de 62,10 a 74,12 %, respectivamente. Por medio de microscopía electrónica de barrido se evidenció que la piel tratada mostró una notable modificación en la textura (Ranjbar et al., 2016). Brat et al., (2001) procesó gulupa mediante expansión instantánea al vacío en comparación con jugo obtenido tradicionalmente: obtuvo un puré con un rendimiento de aproximadamente 50% en peso de fruto, que es el doble contenido del obtenido en el jugo de referencia. También analizaron el color y los polisacáridos de la pared celular de los productos y se midieron propiedades reológicas; el puré obtenido mediante expansión instantánea, era de color rojo-violeta ya que se enriqueció en antocianinas y residuos insolubles en alcohol, razón por la cual, presentó más consistencia y viscosidad, lo que se relaciona con su residuos insoluble en alcohol y contenido de almidón en comparación con el jugo de referencia (Brat et al., 2001). Paranjpe et al., (2012) comparó estudios para comparar el rendimiento y la calidad del jugo extraído de uvas tratadas mediante diferentes procesos (prensado en frio, tratado térmicamente, tratado con enzimas y expansión instantánea al vacío). El proceso de expansión instantánea al vacío, mostró un aumento significativo de contenido de polifenoles totales (g/L) (1.75; 1.97; 2.13; 2.61 respectivamente) y antocianinas monoméricas (mg/L jugo) (190.82; 204.89; 253,23; 315,88 respectivamente), así mismo los rendimientos (g/100 g) de jugo fueron superiores, para los tratados con expansión al vacío, comparados con los tratamientos térmico y prensado en frío (84.3; 75.8; 71.0respectivamente).

Esta tecnología se ha utilizado como un método bastante eficiente para obtener purés de guayaba, mango, aguacate y maracuyá, obteniendo mayores rendimientos, contenido de sólidos solubles, mayor capacidad antioxidante, disminución de pardeamiento e inhibición de enzimas oxidativas (Vargas-Ortiz et al., 2017). Estos resultados son de gran relevancia a nivel industrial para producción de purés de frutas diferenciados de alta calidad.

La ventaja de esta tecnología frente a técnicas convencionales es que asegura el control de la temperatura del producto y del tiempo de tratamiento, ya que además de ser un

tratamiento de tipo HTST, la fase de descompresión a vacío hace que la temperatura del producto disminuya rápidamente permitiendo la obtención de productos de calidad fisicoquímica, microbiológica y sensorial.

2. OBJETIVOS

2.1 Objetivo general

Estandarizar las condiciones operativas de una línea de proceso de flash explosión para la obtención de purés de gulupa y uchuva.

2.2 Objetivos específicos

- Evaluar el efecto de las variables de proceso de Flash explosión sobre los parámetros de calidad fisicoquímicos y microbiológicos de purés de gulupa y uchuva.

- Evaluar la estabilidad durante el almacenamiento de purés de gulupa y uchuva en cuanto a parámetros de calidad fisicoquímicos y microbiológicos

3. INNOVATIVE PROCESS COUPLING SHORT STEAM BLANCHING WITH VACUUM FLASH-EXPANSION PRODUCES IN ONE SINGLE STAGE HIGH-QUALITY PURPLE PASSION FRUIT SMOOTHIES.

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Abstract: Short steam blanching coupled with flash-vacuum expansion (FVE) and de-pulping was used to obtain purée from purple passion fruits discarded from the export chain. Different steam blanching holding times (80, 95, 110 s) were tested at pressure of 130 kPa. After FVE and vacuum de-pulping, fibers, anthocyanins, carotenoids, rheological properties, and microbial reduction were evaluated in the purées. Fruit purées are obtained with a much higher content of cell-wall and bioactive compounds compared to the fresh arils since part of the fruit shell is incorporated into the purée (approximately 20%), which greatly increases the yield of production. Purées exhibited

increasing shear-thinning flow behavior with blanching holding time, resulting in a smoothie-like beverage. A reduction greater than 5 log10 CFU/mL was obtained for molds, yeasts, aerobic mesophilic, and coliforms for all the treatments. The shelf life of smoothies based on nutritional and sensorial quality was extended up to 90 days at refrigeration temperature.

Keywords: hypobaric process; flash pressure release; fruit smoothing process; microbial reduction process

3.1 Introduction

The purple passion fruit (*Passiflora edulis* Sims f. *edulis*) (PPF) is characterized compared to the yellow variety, by its smooth, thick, and purple shell. The pulp is yellow, of subtle flavor with a strong, pleasant, and very recognizable aroma. The fruit contains significant contents of phenolic compounds, vitamins, carotenoids, and fibers mainly concentrated in the shell of the fruit (Medina et al., 2017; dos Reis et al., 2018). Nonetheless, only the juice sacs (arils) are valued which also contain edible seeds and represent only 27% of the whole fruit. Many fruits are rejected by the export market, simply because of their outward appearance, and they are either underutilized or discarded despite their high nutritional value. Post-harvest losses in Colombia, which is one of the largest producers in the world, are between 5 and 10%, which alone amounts to more than 10,000 to 20,000 tons per year. There is an urgent need to valorize this interesting biomass through innovative processing technologies capable of using the whole fruit, preserving the natural bioactive compounds, guaranteeing sensory quality, and ensuring food safety. If traditional thermal processes are very effective in the inactivation of microorganisms, they are often detrimental to the nutritional, functional, and sensory value of foods. For example, the anthocyanins present in the shell of the purple passion fruit are destroyed following a logarithmic curve when the temperature increases arithmetically (Patras et al., 2010).

Nonetheless, with most of the equipment available on a small or medium scale, the objectives of high temperatures and short times are difficult to reach (Al-Ghamdi et al., 2020), which inevitably leads to undesirable effects on the quality of the products. Actually, the main bottleneck for the development of small- and medium-sized agro-food enterprises (SMEs) is the limited supply of appropriate small- and medium-scale technologies to produce very high-quality food products. For this reason, it is important to explore new technologies, to foster greater inclusion of rural agro-food industries while taking into account the growing consumer demand, more focused on quality.

In this context, hypobaric food processing is attracting much interest within agro-food industries mainly because the partial vacuum is quite simple, reliable, and energy-efficient thanks to technological advances in liquid ring vacuum pump technologies (Zhang et al., 2019). Working under reduced oxygen pressure has several advantages in terms of food quality and improved process efficiency. Flash vacuum expansion (FVE), one of the most

promising hypobaric processes, consists of abruptly placing a previously heated biological product under vacuum, which causes instantaneous vaporization of part of the water contained in plant tissues and at the same time induces a sudden cooling of the matrix (Téllez-Pérez., 2019). As an emerging technology, even if the principle is practically the same, the FVE process has been named differently in scientific articles. For example, the expressions “flash-détente” or “détente instantanée controlée (DIC)” which use the French words, have been frequently used as such in international literature, but also flash-release, flash relaxation, or even “instant controlled pressure drop”.

The thermodynamic principle of these processes is based on a very high-pressure drop rate which allows instantaneously and transiently the reduction of the three-dimensional translational motion of particles to two, improving the rate of expansion, the rate of self-vaporization and the cooling rate of the products. Indeed, according to Allaf and Allaf, (Allaf et al., 2014), during this transient period, temperature modification occurs without energy exchange with the external environment and does not respect the classic quasi-static transfer laws. Thus, although very brief, the impact of this hypobaric shock on the quality of the treated product and the energy consumption is notorious. For these reasons, the process has been used efficiently for different operations such as drying, microbial decontamination, reduction of allergenicity of proteins, extraction of chemical compounds among others. So, the aim of this paper was to evaluate the impact of the FVE process on functional compounds, rheology, microbial quality, and shelf life of purple passion fruit purées.

3.2 Materials and methods

3.2.1 Vegetal Material

The Materials PPF discarded from the fresh fruit export market was supplied by AGROJAR SAS enterprise (Jardín, Antioquia, Colombia). Fruits were washed and selected to remove impurities.

3.2.2 Flash-Vacuum Expansion Process (FVE)

The pilot line of the FVE process (Figure 3-1) consists of a cylindrical stainless-steel steam heating chamber (Ø = 154 mm; h = 175 mm, v = 6 L) coupled through a pneumatic valve to a vacuum expansion chamber (volume = 37.5 L) where a rotating pulper/finisher is installed. The pneumatic ball valve that separates the two compartments has a large opening diameter (Ø = 150 mm) and is operated by a rapid pneumatic actuator (80% opening of the valve in 1 s). The equipment is then connected to two aseptic tanks for product and co-product recovery. A liquid ring pump (Robuschi RVS_3 M-02, Parma, Italy) capable of delivering a gas extraction rate of 4200 m^3/h was used to provide vacuum pressures of 5 ± 1.2 kPa inside the chamber. Water vapor is condensed through a heat

exchanger to limit the volume of gas suctioned by the vacuum pump. The vacuum was recorded by a digital vacuum transducer (Sitrans P, Siemens, Germany).

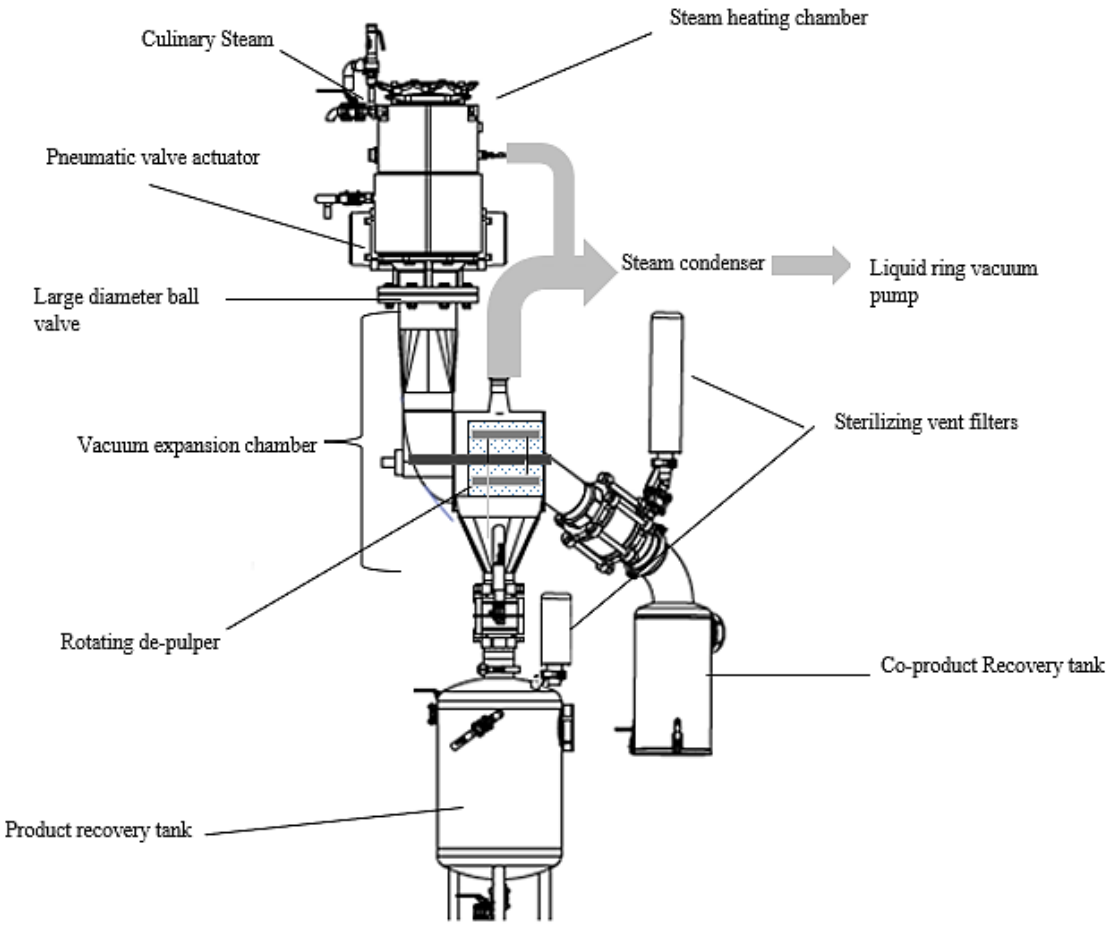

Figure 3-1. Flash-vacuum expansion equipment scheme.

Prior to performing a series of analyses, all equipment is steam sterilized and between analyses, the vacuum is broken through a vented sterilizing filter with an absolute removal rate of air particles of 0.003 µm (Emflon® PFR Filters, Pall, Washington, NY, USA). The whole fruit (1.5 kg per batch = 25 fruits round shape with average diameters of Ø = 5.4 ± 0.2 cm) was deposited in the steam heating chamber, which was submitted to an initial application of vacuum (5 kPa/10 s) (Figure 1). The fruit was blanched with direct injection of steam at a hydrostatic pressure of 130 kPa during different blanching holding times (80, 95 and 110 s). The temperatures, of the heating chamber and at the center of the fruits, were recorded with thermocouples (inserted into the fruits) connected to a data logger (DMCA-1019-2, Maycin, Medellin, Colombia). Four replicates were carried out for each treatment, and a vacuum was applied for 10 s before the fruit was blanched to quickly reach the temperature and thus reduce condensation. Steam admitted in the heating vessel was previously filtered with a culinary filter (0,2 µm pore diameter, PALL, NY, USA) to remove particulates, entrained contaminants, and water in liquid form. After target

holding times were achieved, the steam valve was closed, and the pneumatic ball valve was opened. Immediately fruits fall by gravity into a vacuum expansion chamber through the quick opening of the pneumatic ball valve to produce an instantaneous pressure drop to 5 kPa. While preserving the vacuum inside the chamber, the de-pulper was activated (1500 rpm/30 s) to separate the purée from the husk residues (using mesh size 1.4 mm). Finally, the sieved purée that falls into the storage tank can be pressurized to atmospheric pressure independently of the previous circuit through the vented air-sterilizing filter for the next aseptic or ultraclean packaging step. The purée obtained was immediately packaged in previously irradiated multilayer bags (plasticized, PET/Foil/LDPE 120 microns, murfit Kappa®, Ireland) using a bag-in-box semi-manual filler (Sympaty ROp 320, Technibag, Villefranche-sur-Seine, France). Pouches with fruit purée were stored at 5 °C for analysis, and eventually at 20 °C for study shelf-life stability. The shell and seed fragments were collected and then weighed, and yields were calculated. All the tests were carried out in Rionegro (Antioquia, Colombia) located at an altitude of 2100 m corresponding to an average atmospheric pressure of around 80 kPa.

3.2.3 Physicochemical Characterization

The pH, titratable acidity, and soluble solids were determined by AOAC (AOAC, 2005). standard methods (981.12, 942.15, and 932.12, respectively). Color was determined from CIELAB space (HunterLab ColorFlex EZ spectrophotometer, primary illuminant D65, observation angle 10°). Alcohol Insoluble Residues (AIR) 20 g PPF mash was mixed rapidly in 100 mL 95% *v/v* ethanol, boiled (30 min) and then filtered (158 µm qualitative filter paper, GE Healthcare, Chicago, IL, USA); then, the residue was successively washed with ethanol (80% *v*/*v*) until the sample was completely decolorized. Finally, the residue was dried (50 °C/24 h). The AIR was then washed with plenty of water to remove water-soluble polysaccharides. The residue was dried as described above and weighed for water- and alcohol-insoluble residues (WAIR). Soluble suspended solids (SIS) were evaluated as the percentage by weight of the residue after centrifugation of the PPF purée (10 g at 1000× *g* 20 min) (Brito et al., 2008).

3.2.4 Determination of Anthocyanins

Extraction was performed according to García-Villalba et al. 2015). Purée (1.5 g) was added to 5 mL of the acidic water (1.35% *v/v* HCl), stirred for 30 min at room temperature, and then centrifuged for 10 min (3000 rpm, 20 °C). The supernatant was collected and 4 mL of the methanol/DMSO/acidic water mixture (40:40:20) were added, then it was centrifuged for 10 min (3000 rpm, 20 °C). Finally, the supernatants were collected and brought up to 10 mL with methanol, and the liquid obtained was filtered with a 0.45-µm PVDF membrane (Syringe Filter, Quality Laboratory Supplies, Miami, USA). Anthocyanin content in different purée was determined at 515 nm (Cyanidin 3-*O*-glucoside) by HPLC (Prominence 20, Shimadzu, Kyoto, Japan) equipped with a PDA (SPD-M20A, Shimadzu, Kyoto, Japan) detector. The mobile phase used was 2% formic acid and acetonitrile: water: formic acid (80:18:2). The flow rate was 0.4 mL/min, and the injection volume was 2

µL. A C18 100-Å 5-µm column (250 x * 4.6 mm, Phenomenex Luna) was used, and the column temperature was 30 °C (Mertz et al., 2007). For the calibration curve, the Kromann chloride standard (44689-5MG lot # BCCC0843, Sigma, Merck, Darmstadt, Germany) was used. A stock solution (1 mg/mL) was prepared in mobile phase A. The curve levels were: 0.4, 0.3, 0.2, 0.1, 0.05, and 0.01 mg/mL, obtaining values of R^2 = 0.997 and a retention time of 41.66 min.

3.2.5 Determination of β-Carotene

Extraction was performed according to Franco et al. (Franco et al., 2014); approximately 1 g of sample was mixed with 5 mL of extraction solution (acetone HPLC grade); the mixture was centrifuged (3500 rpm, 10 min), and the supernatant was collected. The pellet was re-extracted with 5 mL of cold extraction solution, and the previous process was repeated. Both supernatants were mixed. Finally, the liquid obtained was filtered (0.45-µm PVDF membrane, Syringe Filter). The quantification was performed on the same analytical platform and with the same type of column described above using a mobile phase consisting of acetonitrile: methanol: acetone (60:30:10) at a flow rate of 1.2 mL/min and separated on a C18. β-Carotene was detected at a wavelength of 450 nm.

3.2.6 Microbiological Analyses and Shelf Life

Culture media were used by the deep sowing method on Petri dishes. Purée (10 g) was mixed with 90 mL of sterile peptone water (0.1% w/v). A 10-fold dilution series was prepared in sterile peptone water for plating. The following culture media and conditions were used to enumerate the microbial cells: 1. Mesophilic aerobic bacteria count (DEV nutrient agar, Merck, Kenilworth, NJ, USA), incubated at 37 °C for 2 days; 2. Mold and yeast (Sabouraud 4% dextrose agar, Merck), incubated at 25 °C for 5 days; 3. Fecal and total coliforms (Chromocult medium agar, Merck), incubated at 37 °C for 2 days. All analyses were performed in triplicate. The results are reported as log CFU/g of the sample (fresh weight, FW). To determine the maximum logarithmic reduction of the process, a batch of fruit was left for several days at room temperature until it reached a high level of contamination. For the evaluation of shelf life, microbiological quality of stored fruit purées was checked every week during storage at 20 °C and every month up to two months during storage at 4 °C and every week thereafter up to 90 days.

3.2.7 Rheology

The effect of FVE on the rheological properties of fruit purée was evaluated by flow curves. An Anton rheometer was used (Paar brand MCR 92, Graz, Austria), together with Rheocompass® software (v.1.20, Anton Paar, Graz, Austria) and a C-CC27 concentric cylinder geometry (27 mm diameter). For the determination of flow behavior, flow curves were obtained according to Zhu et al. (2018) (Zhu et al., 2018). Approximately 20 mL of each sample was taken, and the shear stress (τ) was measured as a function of shear rate

in three phases at 4 °C: an ascending curve (0.01–200 s^{-1} for 60 s), holding time (200 s^{-1} for 120 s), and a descending curve (200–0.01 s^{-1} for 60 s) (Mu et al., 2019). Data from the descending curve were fitted to Herschel Bulkley model (best fit), and the threshold stress (σ0), the consistency index (K), and flow behavior (n) for each FVE process was estimated. The apparent viscosity of the purées was calculated at a shear rate of 50 s^{-1}.

3.2.8 Sensory Analysis

The sensory analysis of purple passion fruit purées was carried out according to ISO 4121, (ISO, 2003). An overall quality assessment was conducted using a 9-point hedonic scale; assessments were made by a trained sensory panel of nine persons. All samples were evaluated independently in a test room complying with ISO 8589, (ISO, 2014) requirements.

3.2.9 Statical Analysis

FVE processes were carried out with 4 replicates (experimental design power of 92%, Design-Expert 11, Stat-ease Inc., Minneapolis, MN, USA). All quality analyses were performed in triplicate, and data are expressed as the mean ± standard deviation. Before ANOVA, normality and homoscedasticity were analysed (Shapiro-Wilk normality and Levene homoscedasticity tests, respectively). Then, ANOVA and Tukey's ($p < 0.05$) test were performed to assess significant differences between treatments. Data analysis was carried out using the statistical software XLSTAT 2022.1.1 (Addinsoft, Paris, France).

3.3 Results and Discussion

Figure 3-2 shows the different steps of the process considering surrounding pressure and temperature at the center of the fruit. In the FVE process, the initial heating of the product is intensified by an initial vacuum (5 kPa) just before injecting high-pressure steam (130 kPa). With this initial vacuum in the heating chamber, heat diffusivity during blanching was considerably increased and the center of the fruit reached target temperatures within few seconds. Holding times of 80, 95, and 110 s in the heating vessel at 130 kPa correspond to approximately 70 °C, 80 °C, and 90 °C, respectively, at the center of fruits recorded by thin thermocouples. For all the temperatures reached in the heart of the fruit during the blanching step, the fruits burst after an instantaneous pressure drop of up to 5 kPa and cool rapidly to reach temperatures measured around 35 ± 5 °C.

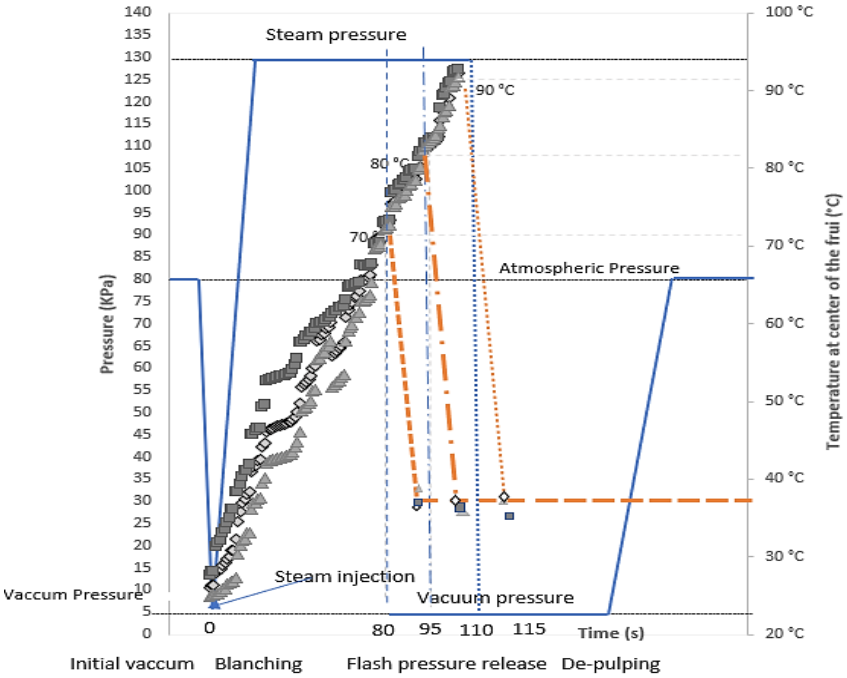

Figure 3-2. Variation of temperature at the center of the fruit and pressure in the neighborhood during flash-vacuum expansion process.

Blue line (-) represents different pressure changes that occur throughout the FVE process; the horizontal gray line (---) represents atmospheric pressure; the vertical blue lines (---) represent the instantaneous pressure drop towards the vacuum of up to 5 kPa after reaching the temperature of each process (70, 80, 90 °C); vertical orange lines (---) represent cooling that occurs rapidly immediately after the instantaneous pressure drop; The horizontal orange line (---) represents the measured temperature around 35±5◦C, after an instantaneous pressure drop; the lines with squares (■),diamonds (◇) and triangles (▲) represent the heating curves that occur in the process at 70, 80 and 90 °C, respectively.

3.3.1. Physicochemical Characterization of Fruit Purée

Following sieving with a pulper/finisher which is done under vacuum, Table 1 shows the yield of the sieved fruit purée which reaches 46%, an increase of about 68% after the FVE compared to the arils (only 27% of the whole fruit). These results agree with Brat et al., (Brat et al., 2001) and prove that part of the fruit shell, approximately 20%, is introduced in the purée after instant pressure drop. No significant differences were found between the yields of purées obtained for different holding times during the blanching carried out before pressure release. This increase in yield in short times by coupling different stages in the production of purées is promising for the application of FVE at an industrial level.

After pressure release and vacuum sieving, intense red color is obtained for the purée fruit, with the incorporation of part of the exocarp. In fact, the parameter a* increased significantly ($p < 0.05$) between the juice proceeding from the arils and all the FVE treatments. In contrast, the contribution of the yellow color expressed through the parameter b* had a significant reduction for all the treatments with respect to the fresh

pulp. The L* parameter linked to brightness decreased (p <0.05) compared to the fresh pulp, but there was no significant difference between the different FVE treatments. Those results agree with Brat et al. (Brat et al., 2001) The color differences between arils and FVE purées could be attributed to the incorporation of anthocyanin from the shell and the dilution of carotenoids from the juice arils. Figure 3-3 shows that the content of cyanidin-3-*O*-glucoside, the most abundant anthocyanin in PPFs mainly located in the fruit shell, increases in fruit purées with the blanching holding time. A content of 14.7, 16, and 20 mg/100 g FP is measured in sieved fruit mash, respectively, for holding times of 80, 95, and 110 s, respectively. The content of 150–170 mg/100 g of cyanidin-3-*O*-glucoside in the PPF shell is slightly higher than previously reported by Ghada et al. (Ghada et al., 2020) and Medina et al. (Medina et al., 2017), but anthocyanins seem to increase with maturity Jiménez et al. (Jiménez et al., 2011) [and Shi et al. (Shi et al., 2021) and could probably be modulated according to cultivars and agricultural practices.

The content of cyanidin-3-*O*-glucoside in the arils is low (5.64 ± 0.060 mg/100 g FP) compared to the content found in the shell. To our knowledge, the presence of anthocyanins in the arils has not been reported before. Only moderate anthocyanin content in Passiflora maliformis seeds has been reported (Méndez-arteaga et al., 2016). Thus, according to these results, the considerably increased anthocyanin content in gulupa purées after the FVE process comes from the shell.

During the heating step, the steam softens the outer part of the fruit and after pressure release, the internal expansion of water vapor creates microchannels that can break down cell walls and facilitate the extraction of bioactive compounds compounds (Brat et al., 2001; Vargas-Ortiz et al., 2017).Through a similar process, Martínez-Meza et al. (Meza et al., 2021) reported at an industrial level, a much higher extraction of extractable polyphenols, from the grape pomace through a similar process.

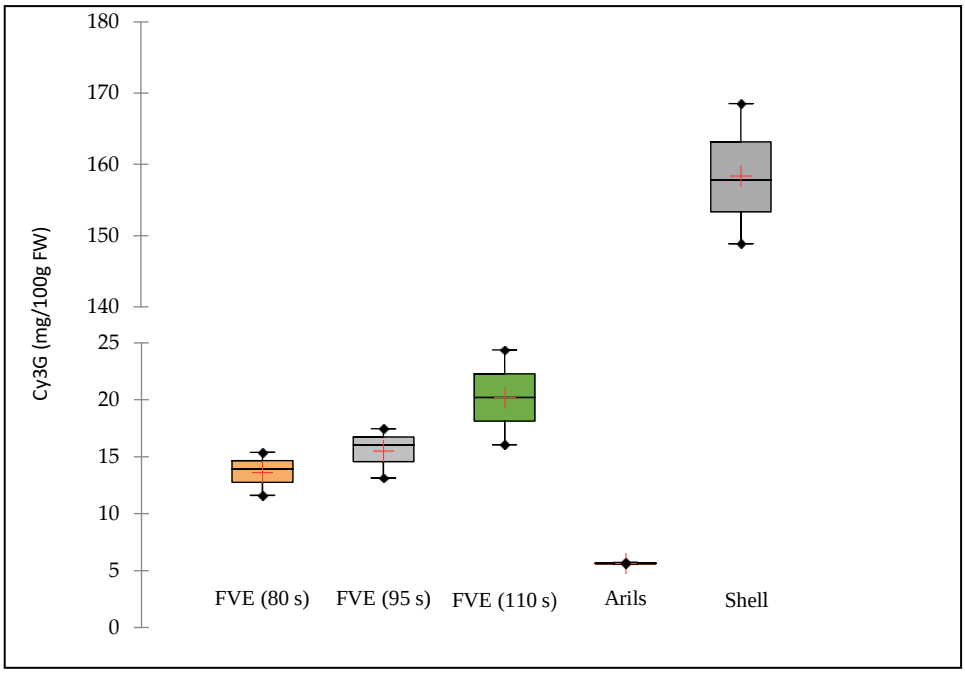

Figure 3-3. Content of cyanidin-3-O-glucoside purple passion fruit purées, arils, and passion fruit shell. Cy3G: cyanidin-3-O-glucoside. FVE: flash-vacuum expansion.

Regarding β-carotene, as observed in Figure 4-3, this compound is more concentrated within arils (13,64 ± 0,63 mg/100 g FW) and after FVE (80 s: 2,69 ± 0,30 mg/100 g FW, 95 s: 2,44 ± 0,16 mg/100 g FW, 110 s: 2,58 ± 0,25 mg/100 g FW), the fruit purée contains a slightly higher amount than the peel (1,64 ± 0,99 mg/100 g FW), but logically, it is still lower than in the arils. For β-carotene, the impact of flash pressure release for different initial temperatures was not significant.

Table 3-1. . Physicochemical characterization of sieved purple passion fruit purée.

Parameters [1]	Arils	Shell	Blanching Holding Time (Seconds)		
			80 s	95 s	110 s
Yield (% *w*/*w*)	27.401 ± 4.539 [a]	-	46.205 ± 4.359 [b]	47.656 ± 2.893 [b]	47.295 ± 5.954 [b]
L*[1]	68.823 ± 0.116 [b]	28.967 ± 0.373 [a]	24.857 ± 1.979 [a]	25.155 ± 0.838 [a]	23.826 ± 2.236 [a]
a*[1]	15.180 ± 0.098 [b]	6.900 ± 0.105 [a]	33.838 ± 2.189 [c]	33.323 ± 3.106 [c]	30.630 ± 5.006 [c]
b*[1]	50.693 ± 0.144 [c]	3.020 ± 0.234 [a]	24.153 ± 3.938 [b]	23.673 ± 4.999 [b]	21.638 ± 5.663 [b]
SS [2] (gxL^{-1})	15.667 ± 0.208 [b]	-	10.125 ± 2.016 [a]	10.875 ± 2.529 [a]	10.425 ± 1.338 [a]
Acidity (% citric acid)	3.025 ± 0.076 [c]	-	2.483 ± 0.046 [b]	1.624 ± 0.201 [a]	1.690 ± 0.110 [a]
pH	3.137 ± 0.047 [a]	-	3.183 ± 0.128 [a]	3.108 ± 0.061 [a]	3.151 ± 0.044 [a]
SIS [3] (g/100 g FW)	25.686 ± 1.508 [a]	-	38.065 ± 1.687 [b]	100 ± 0.000 [c]	100 ± 0.000 [c]
AIR [4] (g/100 g FW)	2.432 ± 0.380 [a]	-	2.205 ± 0.075 [b]	4.293 ± 0.054 [c]	5.486 ± 0.078 [d]
WAIR [5] (g/100 g AIR)	54.927 ± 1.514 [a]	-	78.370 ± 0.253 [b]	30.076 ± 5.774 [c]	14.477 ± 1.612 [d]

[1] Color coordinates in the CIELAB space: L*: luminance, i.e. lightness [0-100], a*: >0: red, < 0: green, b*:>0: yellow, < 0: blue. [2] Soluble solids. [3] Suspended insoluble solids. [4] Alcohol-insoluble residues. [5] Water-insoluble alcohol-insoluble residues. Values are presented as the mean ± standard error, *n* = 3, different letters in each row indicate that there is a statistically significant difference (p <0.05), FW: fresh weight.

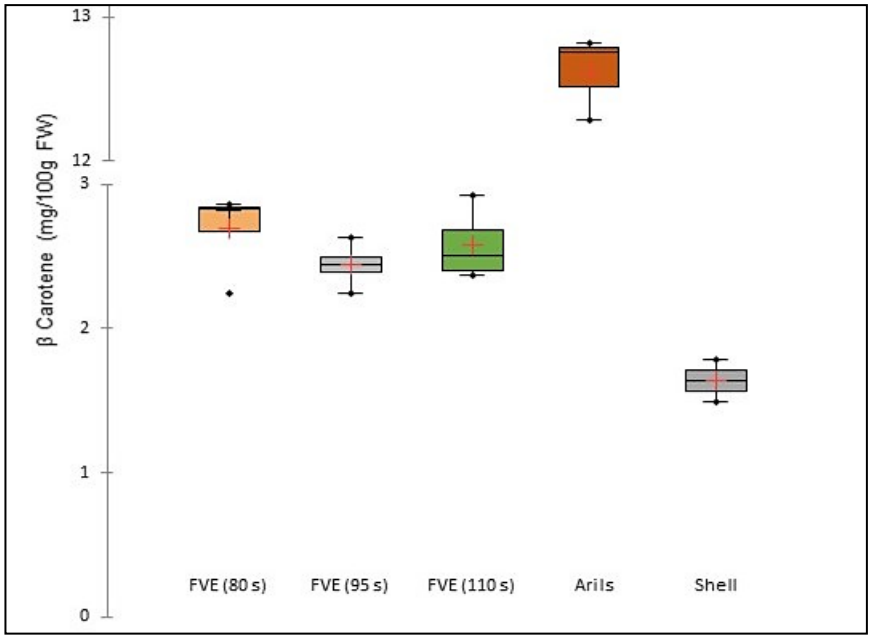

Figure 3-4. Content of β-Carotene in purple passion fruit purées, arils, and passion fruit shell. FVE: flash-vacuum expansion. FW: fresh weight.

The process also had an impact on the content of suspended insoluble solids (SIS), AIR and WAIR measured on sieved fruit purée (Table 3-1). SIS and AIR include soluble and insoluble pectin, cellulose, hemicellulose, lignin, and possibly native starch granules which are present in passion fruit even at the mature stage increase almost 4 to 2 times between 80 and 110 s of the blanching holding time, respectively (Brito et al., 2008). It proves once again that FVE causes partial disintegration of the PPF shell allowing incorporation into the fruit purée of part of cell wall fragments. WAIR, which includes all anterior cell-wall compounds except hydrosoluble pectin, decreases between 80 and 110 s of blanching holding time, meaning that incorporation of soluble pectin increases dramatically. The composition of SIS, AIR, and WAIR in fresh arils differs from fruit purée because the arils contain edible seeds and native starch granules (Brat et al., 2001), which may explain their relatively high SIS content, AIR and WAIR (Table 3-1). After the FVE process, with blanching temperature superior to 80 °C at the center of the fruit (holding time 95 s), the incorporation of soluble pectin into the purée increases dramatically. The percentage of soluble pectin in purées obtained after 90 and 110 s of blanching is 1.3% and 4.66%, respectively, which is very high (in Table 3-1, the soluble pectin corresponds to the weight lost by the AIR after washing with water).

3.3.2 Rheology of the Sieved Fruit Purée Obtained

As observed in Table 2, the sudden impact of the vacuum expansion affected the rheological behavior of the different fruit purées obtained after sieving under the same conditions. The “n” value of all fruit purées, less than 1, describes a shear-thinning flow behavior. A significant effect of the blanching temperature at the center of the fruit is observed on n, K and the apparent viscosity ($p < 0.05$) for all the fruit purées obtained, but the impact increases considerably after flash-vacuum relaxation. After the instantaneous vacuum-release, the apparent viscosity at the oral shear rate often adopted for the measurement of free-flowing foods (50 s^{-1}) (Soukoulis et al., 2014), was increased 4, 10, and 130 times for 80, 95, and 115 s blanching holding time, respectively (corresponding to 70 °C, 80 °C and 90 °C at the center of the fruit), giving an increasing “smoothie” character to fruit purées. The fruit purée obtained only after blanching, in addition to a much lower yield after sieving, has a more Newtonian behavior and a lower apparent viscosity. In this context, the repercussions of the process on the rheology relate not only to the sensation in the mouth of a smoothie-type creamy consistency but also to the fact that the product becomes spoonable. This behavior is mainly explained by the incorporation of soluble pectin and the gelatinization of the starch. After FVE the starch granules gelatinized because the gelatinization temperature range of PPF starch granules is 58–66 °C (KWOK et al., 1974).

Table 3-2. Rheological parameters of different purple passion fruit purées.

Sample	n (-)	K (mPa x·s^n)	r^2	Viscosity to σ: 50 s^{-1} (mPa x ·s)
Juice arils	0.692 ± 0.005 [a]	0.057 ± 0.006 [a]	0.994 ± 0.001	17.012 ± 1.409 [a]
80 s only blanching	0.874 ± 0.048 [c]	0.003 ± 0.000 [a]	0.960 ± 0.030	1.869 ± 0.345 [a]
95 s only blanching	0.734 ± 0.068 [ab]	0.145 ± 0.004 [a]	0.973 ± 0.018	51.859 ± 12.167 [a]
110 s only blanching	0.707 ± 0.068 [ab]	1.560 ± 0.004 [c]	0.963 ± 0.018	495.931 ± 12.167 [c]
80 s with flash-expansion	0.767 ± 0.019 [b]	0.168 ± 0.074 [ab]	0.981 ± 0.003	68.734 ± 34.975 [ab]
95 s with flash-expansion	0.720 ± 0.044 [ab]	0.477 ± 0.053 [b]	0.976 ± 0.002	158.934 ± 9.936 [b]
110 s with flash-expansion	0.581 ± 0.002 [d]	10.698 ± 0.114 [d]	0.926 ± 0.001	2078.199 ± 6.668 [d]

Mean ± standard error, n = 3, different letters in each column indicate that there is a statistically significant difference ($p < 0.05$). Average flow behavior (n); average consistency index (K). Note: rheological parameters were validated at refrigeration temperature (4 °C).

3.3.3 Microbiological Quality and Shelf-Life Stability

The fresh (untreated) purées of purple passion fruit presented a count of mesophilic aerobic microorganisms, molds and yeasts, total and fecal coliforms of 3.0, 3.0, and 0 log CFU/g, respectively. After the FVE process, the microbial counts were always below the detection limit for all the microorganisms evaluated in all the treatments.

Nonetheless, to evaluate maximum logarithmic reduction, fruits highly contaminated above 5 log CFU/g, were treated and it was shown that the FVE process allows at least logarithmic reduction of 5, 5, and 7 log CFU/g, for aerobic bacteria, mould and yeasts, and total coliforms, respectively. For thermal holding time over 80 s in the heating vessel at 130 kPa combined with instant pressure release at 5 kPa, a final microbial count under the limit of detection is obtained for all microorganisms analyzed. The process with fruits at 80 s in the heating vessel reduced the microbial load by at least 5 log10 CFU/mL and fruit purées can be considered as commercially sterile similarly to other thermal processes such as UHT and HTST. According to Téllez-Pérez et al. (Téllez-Pérez., (2019), thermal stress impacts (short-time heating and instant cooling) seem to be very effective in the destruction of microorganisms. Moreover, the decontamination is also probably due, not only to the almost instantaneous cooling but also to the sudden drop in pressure, which may cause an effect of the explosion of the cells of microorganisms (spores or vegetative forms). This instantaneous pressure change affects the cells of microorganisms and causes irreversible changes to occur, such as denaturation of the cells, proteins, and cell membrane rupture (Mazen Hamoud-Agha & Allaf, 2020).

Regarding the shelf-life stability of smoothies that were “ultra-clean” packaged, microbiological quality monitoring revealed no growth after 90 days of storage for aerobic bacteria, mold and yeasts, and total coliforms. Nonetheless, the determination of the shelf

life of these products cannot be based solely on the microbiological quality and the content of residual anthocyanins and β-carotene has been evaluated during storage. As can be seen in Figure 3-5, the reduction in the content of the two main bioactive compounds is notorious when the product is stored at 20 °C. For which the half-life can be established at around 15 days. During storage at refrigeration temperature, the destruction of the two bioactive compounds is slower and an acceptable content is reached after 90 days, which is also reflected in the acceptance deemed satisfactory by the sensory analysis of a trained panel (Figure 3-6).

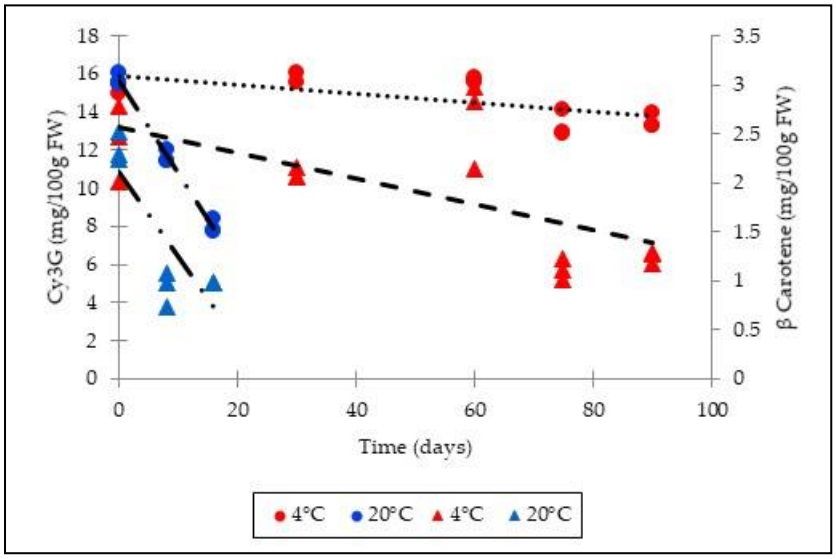

Figure 3-5. Stability of cyaniding-3-glucosides and β-carotene during storage of smoothies obtained by flash-vacuum expansion process at different temperature (cyanidin-3-O-glucoside and beta carotene are represented by circles and triangles, respectively). Cy3G.

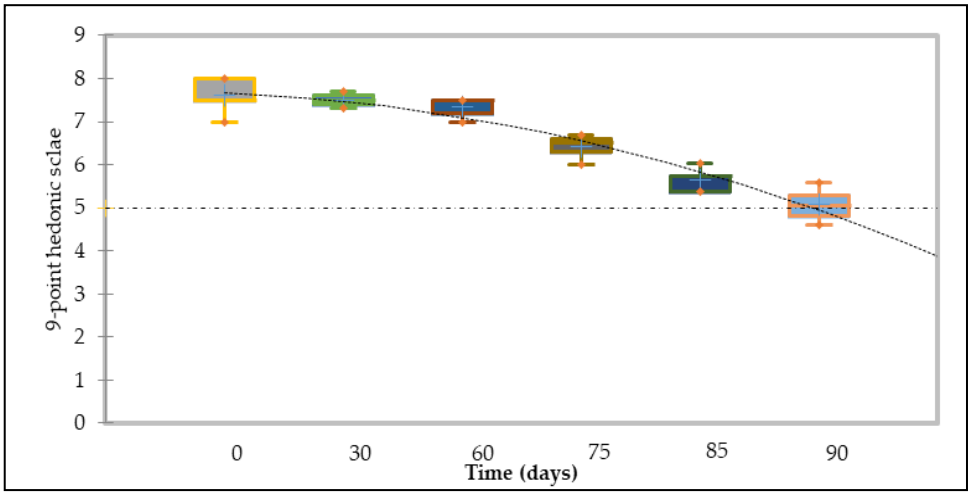

Figure 3-6. Overall global quality estimates through sensorial analysis during storage at 4 °C of flash-vacuum expansion smoothies.

3.3.4 Considerations on Energy Saving and Investment Costs

In terms of time-temperature curve of the product, the system is similar to a classical high-temperature short-time process (HTST) (Figure 2). The blanching and heating phase of pasteurization occurs here in a single step, which saves energy compared to conventional processes that require separate unit-operation such as whole fruit blanching, cooling, and pulping followed by pasteurization of fruit purée. Additionally, the thermal efficiency of direct steam injection is higher than that of indirect systems with exchangers used during classical pasteurization of fluids.

On the other hand, the major result of the process is the rapid cooling of fruit purées after flash-vacuum expansion. This instant cooling from the target blanching temperature to 35 ± 5 °C requires only the energy consumption of the liquid ring vacuum pump, the condensation of water vapor in a heat exchanger, and the power necessary for the quick opening of the valve. The energy consumption of the liquid ring vacuum pump is relatively low (Miladi et al., 2020), as well as for the opening of valve and condensation of water vapor. On the other hand, very large surface heat exchangers are required in conventional HTST processes applied to viscous fruit purées, which are very expensive to build, but also have a high overall energy consumption because their performance depends on the surface but also on the high speed of the fluid for good forced convection and a sufficiently turbulent flow which must be ensured by often oversized pumps. Additionally, it should be added the energy consumed by limiting factors such as fooling, scaling, clogging, maintenance, and cleaning in place. Undoubtedly, the equivalent heat exchanger infrastructure to provide the same time–temperature curve for product during FVE would be very expensive and energy intensive. Therefore, in addition to the energy saving expected, the process represents a major reduction in equipment costs over classical HTST while having similar quality benefits and being viable at small and medium scale.

3.4 Conclusiones

The study demonstrates that short steam blanching (80, 95, and 110 s) coupled to flash-vacuum expansion (FVE) and vacuum de-pulping process increases the yield production of PPF purée at least twice due to the incorporation of a part of the exocarp. The disruption of the fruit cellular tissue of the shell due to the effect of the FVE process increases the content of bioactive compounds such as anthocyanins. In addition to these bioactive compounds, there is also migration mainly of the water-soluble pectin of the shell towards the purées but also of other compounds of the cell walls such as insoluble pectin, cellulose, hemicellulose, and lignin. After FVE and vacuum sieving, the fruit purées take on a creamy smoothie-like consistency and the product becomes spoonable and can be used as baby food, toppings, sugar-free fruit-rich compote, among others. Regarding the effect of the FVE process on the microbial quality of the purées, the results show a logarithmic reduction between 5 and 7 log CFU/g even for the shortest heating period (80 s). The PPF purées obtained by FVE did not present a microbial count after 90 days of storage at 4 °C.

In general, we can conclude that the FVE process allows the decontamination of the product while incorporating bioactive compounds and cell walls of the shell, which gives the product a smoothie-like texture highly appreciated by potential consumers. This is obtained without human intervention from the whole fruit to the smoothie, by carrying out in a single equipment five unit-operations: blanching, pasteurization, deaeration, cooling, and de-pulping, all this following a time–temperature curve very similar to the classic HTST process.

Patents

Authors declare a patent related to the published work is in the protection process (Dispositivo para la producción de purés, néctares o extractos de material vegetal NC2021/0016741 Superintendencia de industria y comercio).

Author Contributions: C.A.: Methodology, Formal analysis, Writing—original draft. P.R.: Conceptualization, Methodology, Data curation, Formal analysis, Supervision, Project administration, Funding acquisition. M.C.: Writing—review and editing. I.S.: Methodology, Formal analysis, Writing—original draft. J.Q.: Methodology, Formal analysis. F.V.: Conceptualization, Methodology, Data curation, Formal analysis, Supervision, Funding acquisition. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement: Not applicable

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Data Availability Statement: The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Conflicts of Interest: The authors declare no conflict of interest. The data that support the findings of this study are available from the corresponding author upon reasonable request.

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4. FLASH-VACUUM EXPANSION, A LOW COST AND ENERGY-EFFICIENT ALTERNATIVE PROCESS TO PRODUCE HIGH QUALITY FRUIT PUREE: APPLICATION TO *Physalis peruviana* L.

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Abstract

Goldenberry has a great potential for the development of high-quality products due to its attractive sensory attributes, bioactive compounds, and health benefits. However, postharvest losses are high due to the lack of processing technologies that can both be adapted to rural conditions in producing countries to generate high-quality products. Flash-vacuum expansion (FVE) coupled with vacuum pulping is a new process that can meet these requirements. FVE was carried out at different holding times of steam blanching (30, 40, and 50 s/130 kPa) with or without the application of flash-vacuum expansion at 5 ± 1.2

kPa. The logarithmic reduction of microbial load and some quality indicators, such as β-carotene content and ascorbic acid (AA), were analyzed during the process and during storage to assess the shelf life of fruit purees. The total energy consumption of all subsystems was then assessed. The FVE process with 40 s steam blanching led to a microbial reduction of over 6 log CFU/g, increased yield and β-carotene content and preserved most of the AA content (4-12%). Based on the half-lives of the quality indicators, the shelf life of the purées was between 16 d (20 °C) and 90 d (4 °C). The energy consumption was estimated at approximately 0.30 kWh/kg of product. These results demonstrate that the FVE process, although it includes a heat treatment, allows a short exposure to heat of the whole fruits to obtain a high-quality puree with an adequate shelf life in a single step, with a relatively low equipment investment and moderate energy consumption.

Keywords: *Physalis peruviana*, functional foods, flash vacuum expansion, bioactive compounds, innovative technology, shelf life.

4.1 Introducción

Goldenberry (*Physalis peruviana* L.) is an exotic fruit belonging to the Solanaceae family native to South America. It has been given multiple names around the world; in Colombia, it is known as “uchuva”, and in English-speaking countries, it is known as “goldenberry” or Cape gooseberry. The fruit is a berry contained in a shell called a calyx. The fruit has a diameter between 1.25 and 2.50 cm, an average weight of 4 to 10 g, a smooth, waxy, orange–yellow skin and a juicy pulp containing numerous small seeds (Olivares-Tenorio et al., 2016). Its production extends throughout the South American Andes. There is great interest in the consumption and industrial use of this fruit for its nutritional and medicinal properties (Ramadan & Moersel, 2007; Repo de Carrasco & Encina, 2008; Rop et al., 2012; Valdenegro et al., 2010, Vega-Gálvez et al., 2014; Salazar et al., 2008; Ballesteros-Vivas et al., 2019), as well as for its functional value for health, as shown recently for insulin signaling to reduce the risk of type 2 diabetes (Vaillant et al., 2021).

Colombia is one of the main exporting countries in the world (around 7800 Ton 1700 ha in 2021), mainly to the European and US markets. The shelf life of fresh fruits is strongly affected by fungal growth, which affects the loss of firmness, increase in maturity index and weight loss during storage (Olivares-Tenorio et al., 2017). Within the export chain, postharvest losses are estimated to be between 28-43%. Immediately after harvest, between 10-15% of fruits are discarded due to cracking or other visual defects (Md Nor & Ding, 2020). For these reasons, the transformation of fruits rejected from the export market is a fundamental issue to increase the competitiveness of the value chain. However, this requires the development of viable innovative technologies at the level of small and medium agro-industries because production is dispersed in developing countries, and at the same time, they must obtain quality products with an appropriate shelf life to reach diversified markets.

Among the innovative technologies that have been studied for the transformation of goldenberry is high hydrostatic pressure (HHP) (Ferrari et al., 2010), (Huang et al., 2013), (Vega-Gálvez et al., 2014), but implementation in developing countries is difficult due to very high investment costs. The potential of FVE technology for the development of high-quality fruit purees has been demonstrated for passion fruit processing (Arias et al., 2022), (Brat et al., 2001), and this technology is attracting much interest due to its low investment cost and its relatively low energy requirements, which can promote its use in small and medium agro-industries in rural areas of developing countries.

The principle of the FVE process is based on the disintegration of plant tissues by the combined effect of blanching and the application of sudden vacuum. The raw material is placed in a heating chamber with saturated steam at 130 kPa and then quickly subjected to partial vacuum pressure (2-5 kPa) in an expansion chamber. This expansion generates the instantaneous evaporation of part of the water contained in the plant tissues, causing the cells to burst. By coupling vacuum pulping to the latter, the FVE process makes it possible to obtain a high-quality fruit puree in a single step (Arias et al., 2022). The application of this process to different fruits is required to better understand the technology and its limitations. The optimization of the process parameters, the determination of the impact on the quality and the shelf life of the finished products and a better evaluation of the specific energy consumption are challenges that we propose to explore in this article, choosing goldenberry as an example of application.

Nomenclature	**Subtract**
D: cross-sectional diameter of fruit (m)	p Fruit purée
Cp: specific heat of the fluid ($J.kg^{-1}.K^{-1}$)	f fruit
λ: Thermal conductivity ($W.m^{-1}.K^{-1}$)	steam
P: pressure (Pa)	k number of subsystem
q: effective heat flux ($kW.m^{-2}$)	t time
Thermal diffusivity = $m^2.s^{-1}$	tp time of operation
ρ: Specific mass ($kg.m^{-3}$)	w liquid water
ΔH_{fg}: change of enthalpy	0 Ambient temperature
T: time	sb Steam blanching
η: Efficiency of the boiler (80%)	st storage
λ:Thermal conductivity ($W.m^{-1}.K^{-1}$)	
Q: heat source ($W.s^{-1}$)	
m: mass flow ($kg.h^{-1}$)	
T: temperature of fruit or pur´ee (◦C)	
H_{fg}: The specific enthalpy of evaporation of steam (KJ/kg)	
κ: rate constant of 1st order kinetic reaction (day^{-1})	
t ½: half-life time	
BI: Browning index	
m_{steam}: steam: Steam flow ($kg.h^{-1}$)	
μ: Velocity of surface $m.s^{-1}$	

4.3 Materials and methods

4.3.1 Vegetal material

The fruits used were discarded from the export chain according to the export classification criteria of the company Caribbean Exotic (Rionegro, Antioquia-Colombia). Fruits reached a state of maturity between 4 and 6, which correspond to light orange, orange, and intense orange peel colors, respectively NTC 4580 (ICONTEC, 1999). Before the process, the calyx was manually eliminated, and the fruits were washed and sorted to remove unripe (green skin color) and foreign material.

4.3.2 Flash-vacuum expansion process (FVE)

Goldenberry purées were obtained using a pilot line of FVE constituted by a cylindrical stainless-steel chamber (Ø=154 mm; h= 175 mm, v= 6 L), connected to an expansion chamber (volume= 37.5 L), coupled to a rotating pulper/finishing. Between the heating and vacuum chambers, there is a large opening diameter ball valve (ø=150 mm), which allows the passage of the material using a fast pneumatic actuator (80% opening of the valve in 1 second). The vacuum was generated by a liquid ring pump (Robuschi RVS_3 M-02, Parma, Italy) capable of delivering a gas extraction rate of 4200 m^3/h, providing a vacuum pressure of 5 ± 1.2 kPa inside the expansion chamber. Water vapor is condensed through a heat exchanger to limit the volume of gas suctioned by the vacuum pump. The vacuum pressure was recorded by a digital vacuum transducer (Sitrans P, Siemens, Germany). Inside the vacuum chamber, a rotary pulping system (1500 rpm/30 s) was set up to sieve the fruit puree on 1 mm meshes. Two aseptic tanks allow the recovery of sifted fruit purées and coproducts such as seeds and large fragments. The whole pilot line of FVE was steam sterilized before the process and between each treatment. The vacuum was broken through a vented sterilizing filter with an absolute air particle removal rate of 0.003 µm (Emflon® PFR Filters, Pall, Washington, NY, USA).

Whole goldenberry fruits (1.5 kg per batch) were introduced into the steam heating chamber, and then an application of vacuum at 5 kPa/5 s was performed for initial degassing. After that, steam previously filtered with a culinary filter (0.2 µm pore diameter, PALL, Washington, NY, USA) was injected directly, maintaining a hydrostatic pressure of 130 kPa inside the heating vessel for different holding times of 30, 40, and 50 s. During blanching, a valve at the bottom of the heating tank remained partially open to permanently evacuate the condensates and promote a minimum flow of steam. After achieving the holding time target, the steam and condensate valves were closed, and the pneumatic ball valve was suddenly opened. The fruits then passed immediately by gravity into a vacuum expansion chamber undergoing an instantaneous pressure drop to 5 kPa.

When only steam blanching (SB) was performed, the fruits fell into the same chamber, and the mash was sieved, but this all occurred without implementing vacuum suction (Fig. 1).

Finally, the sieved purée that fell into the storage tank could be pressurized to atmospheric pressure independently of the previous circuit through the vented air-sterilizing filter for the next ultraclean packaging step. The obtained purée was immediately packaged in previously irradiated multilayer bags (plasticized, PET/Foil/LDPE 120 microns, Smurfit Kappa®, Dublin, Ireland) using a bag-in-box semimanual filler (Sympaty ROp 320, Technibag, Villefranche-sur-Seine, France) set up inside a laminar flow hood. Four replicates were made for each treatment. It is worth noting that the experiments were carried out at 2100 m.a.s.l. in AGROSAVIA's pilot plant in Rionegro (Antioquia, Colombia), corresponding to an average **atmospheric pressure of approximately 80 kPa-**

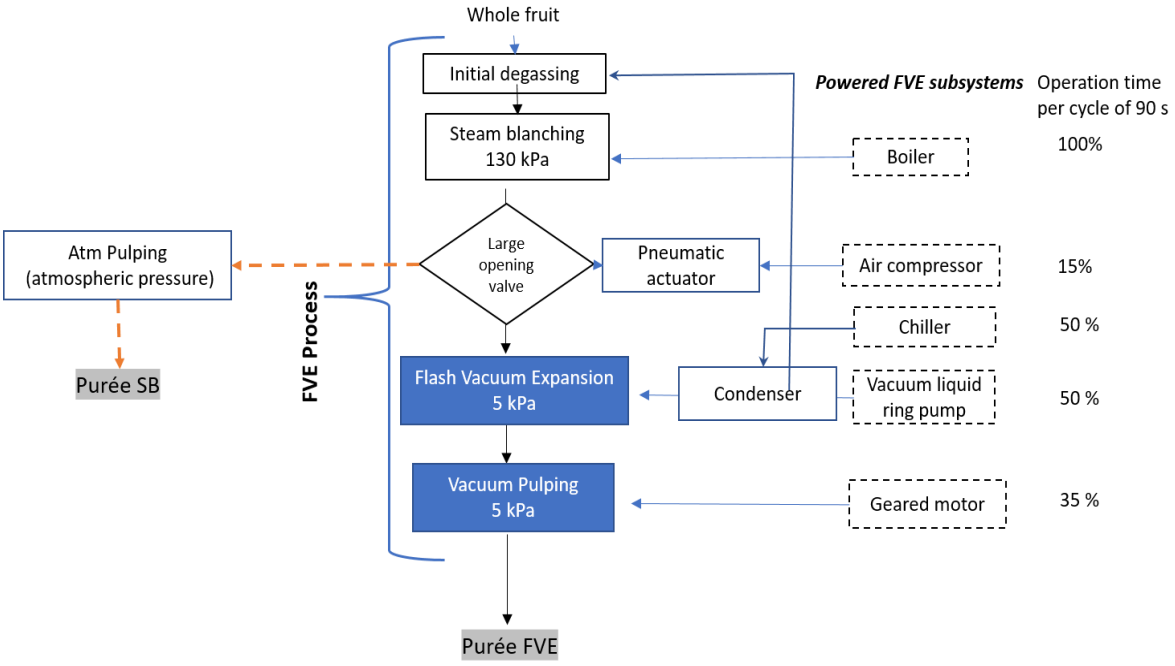


Figure 4-1. Flow diagram of the flash vacuum expansion process and powered subsystems.

4.3.3 Study of heat transfer

In the heating chamber, the temperatures of the environment and the fruits were recorded using probes by a data logger (DMCA-1019-2, Maycin, Medellín, Colombia). The temperature inside the central region of 3 fruits, placed in the middle of the whole fruit mass, was detected by flexible probes (diameter 1 mm). Additionally, a numerical simulation of heat transfer was solved in by COMSOL Multiphysics (v5.6), taking into account the high sphericity of the fruit (97% according to (Hidayat et al., 2021) and an average equatorial diameter of fruits of D=17.5x10-3 m. The geometry was simulated as a 2 D axis symmetric sphere. In the absence of reliable published thermal properties of *Physalis peruviana*, data from tomato, another Solanacea, were chosen to approximate heat transfers with heat capacity Cp = 2.750 kJ.kg-1. K-1 and λ = 0.5 W.m-1. K-1

(Ekpunobi, U. et al., 2014). The specific mass ρ1100 kg.m-3) was reported for *Physalis peruviana* by Oliveira et al. 2016 (Oliveira et al., 2016).

The heat transfer equation used for the COMSOL simulation was:

$$\rho\, C_p \frac{\delta T}{\delta t} + \rho C_p\, u\nabla T = \nabla.(\lambda \nabla \mathrm{T}) + \mathrm{Q} \qquad \textbf{Eq. 4-1}$$

For the simulation, it was assumed that the steam is renewed at such a high rate that the surface of the fruit in the chamber is instantly at the same temperature as the incoming steam. Moreover, since the fruit of interest is in the center of the chamber, direct contact with the vapor is negligible, which allows heat transfer to be applied by conduction alone without the need to add convection.

4.3.4 Physicochemical analysis

The yield was determined by the ratio of the mass of fruit puree obtained after sieving relative to the total mass of treated fruit. The pH, titratable acidity, and soluble solids were analyzed according to the standard methods of the AOAC 2005 (No 981.12, 942.15, and 932.12, respectively). Color was determined using a Color Flex EZ spectrophotometer (Hunter Lab, illuminant D65, observation angle 10°), and the results were expressed in the CIELAB color space. L* represents brightness or dullness in the range of 0–100, and a* and b* represent redness (+)/greenness (-) and yellowness (+)/blueness (-), respectively. The values of the total color differences (ΔE*), chroma (Cab), and hue (h°ab) were determined using the equations:

$$\mathbf{\Delta E^*} = \sqrt{\mathrm{L^*}\text{-}L_0)^2 + (a^* - a^*_o)^2 + (b^* - b_0)^2} \qquad \textbf{Eq. 4.2}$$

$$\mathbf{C_{ab}} = (a^{*2} + b^{*2})^{\frac{1}{2}} \qquad \textbf{Eq. 4-3}$$

$$\mathbf{h_{ab}} = \tan^{-1}\left(\frac{b^*}{a^*}\right) \qquad \textbf{Eq. 4-4}$$

Where L^*_0, a^*_0, and b^*_0 represent the initial values of L*, a*, and b*, respectively, immediately after processing at 0 days of storage. The browning index (BI) is calculated from the CIE L*a*b* coordinates by applying the equation given by Buera et al. 1986:

$$\mathbf{BI} = \frac{100\,(x - 0.31)}{0.17} \qquad \textbf{Eq. 4-5}$$

Where x:

$$x = \frac{(a^* + 1.75L^*)}{(5.645L^* + a^* - 0.012b^*}$$ **Eq. 4-6**

4.3.5 β- carotene

Extraction was performed following the method published by Etzbach et al. (2018) with some modifications. Briefly, approximately 1 g of sample was mixed with 10 mL of extraction solution (hexane: acetone 60:40); the mixture was centrifuged (3500 rpm, 5 min, 4 °C), and the supernatant was collected. Finally, the liquid obtained was filtered (0.45-µm PVDF membrane, syringe filter). The quantification was done in an HPLC (Prominence UFLC 20A, Shimadzu, Kyoto, Japan) equipped with a PDA (SPD-M20A, Shimadzu, Kyoto, Japan) detector and a Luna® C18 column (2) 100 Å (250 mm* 4,6 mm ID* 5,0 µm) (Phenomenex Luna, Torrance, CA, USA). Carotenoids were eluted using a mobile phase consisting of acetonitrile: methanol: acetone (60:30:10) at a flow rate of 1.2 mL/min and separated on a C18 column. The chromatograms were processed at 450 nm, and carotenoids were quantified as β-carotene equivalents using an external calibration curve (β-carotene standard (Sigma Aldrich C4582) (0.4–0.01 mg/mL), R^2 = 0.999, and retention time 19.52 min. The results are expressed as mg of β-carotene/100 g of fresh weight FW).

4.3.6 Ascorbic acid

The extraction and identification of ascorbic acid was carried out according to the methodology described by Lee et al. (2016) with some modifications, as described below (Lee et al., 2016). Approximately 3 g of purée was weighed, 20 mL of a KH_2PO_4 solution (0.02 M, pH: 3.06 adjusted with 85% ortho-phosphoric acid) was added, and the mixture was stirred at room temperature (20 °C) for 1 min at a speed of 3000 rpm with a vortexer (Analog vortex mixer, VWR; Avantor delivered by VWR, United States). Subsequently, it was centrifuged at 4 °C for 15 minutes at 3000 rpm, and the supernatant was filtered using a 0.45 µm PVDF syringe filter. Identification and quantification were performed by HPLC (Prominence UFLC 20A, Shimadzu, Kyoto, Japan) coupled to a Prominence SPD-M20A diode array detector with a Luna® C18 column (2) 100 Å (250 mm* 4.6 mm ID* 5, 0 µm) and with a mobile phase of the same extraction solution. The analysis conditions were mobile phase flow rate 1.0 mL/min, temperature 35 °C, injection volume 20 µL, absorption wavelength at 244 nm, and isocratic mode. The concentration of ascorbic acid in the purées was determined by the external standard method using an ascorbic acid standard curve (Sigma Aldrich 47863) (0.1–50 µg/mL), R^2 = 0.999, and the retention time was 4.37 min. The results were expressed as mg ascorbic acid/100 g purée on fresh weight (FW).

The degradation rates of ascorbic acid (AA) and β-carotene were fitted to first-order reaction kinetics, and the equation for this model is:

$$A_t = A_0 * \exp(-\kappa t_{st}) \quad \textbf{Eq. 4-7}$$

Where A_0 is the initial content and A_t is the content after storage time. The half-life ($t_{1/2}$) is the time needed for 50% degradation of AA or β-carotene and was calculated using the equation:

$$t_{1/2} = Ln2/k \quad \textbf{Eq. 4-8}$$

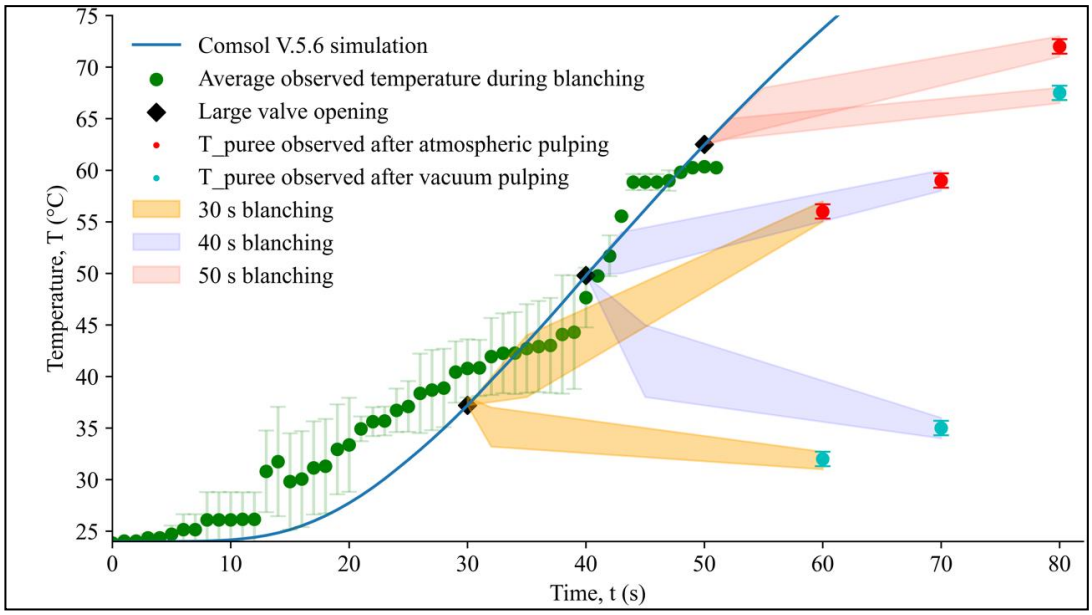
4.3.7 Microbiological analyses

Culture media were used by the deep sowing method on Petri dishes. Purée (10 g) was mixed with 90 mL of sterile peptone water (0.1% w/v). A tenfold dilution series was prepared in sterile peptone water for plating. The following culture media and conditions were used to enumerate the microbial cells: 1. Mesophilic aerobic bacteria count (DEV nutrient agar, Merck), incubated at 37 °C for 2 days; 2. Mold and yeast (Sabouraud 4% dextrose agar, Merck), incubated at 25 °C for 5 days; 3. Fecal and total coliforms (Chromocult medium agar, Merck), incubated at 37 °C for 2 days. All analyses were performed in triplicate. The results are reported as log CFU/g of the sample (fresh weight, FW). To determine the maximum logarithmic reduction, a batch of fruit was left for several days at room temperature until it reached a high level of contamination.

4.3.8 Statistical analysis

Holding times in the heating chamber and vacuum expansion (FVE) were used as factors in the full factorial (3x2) randomized experimental design. Heating-up times of 30, 40, and 50 s were applied with or without flash vacuum expansion. The treatments were defined as steam blanching (SB) for heating without vacuum application and flash vacuum expansion (FVE) when vacuum was applied after each heating-up time. Four replicates were tested to guarantee an experimental design power of 92% (Design-Expert 11, Stat-ease Inc.). All quality analyses were performed in triplicate and randomized, and the data are expressed as the mean ± standard deviation. Before ANOVA, normality and homoscedasticity were analyzed (Shapiro–Wilk normality and Levene homoscedasticity tests, respectively). Then, ANOVA and Tukey's ($p < 0.05$) test were performed to assess significant differences between treatments. For the shelf life, a repeated measures ANOVA was established ($p < 0.05$). Nonlinear regression analysis was performed according to the first-order model equation, and the goodness of fit was estimated (R2). Data analysis was carried out using the statistical software XLSTAT 2022.1.2 (Addinsoft).

4.4 Results and discussion



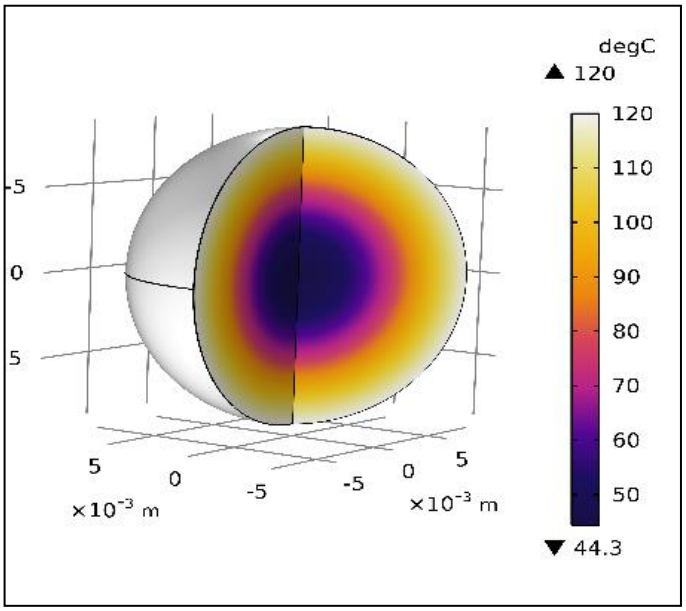


Figure 4-2. a. Average temperature profile at the center of fruits during different steam blanching holding times with or flash vacuum expansion (FVE) or without (SB) and b. Along the cross-section of an average fruit after 40 sec blanching with steam at 130 kPa.

Figure 4-2a shows the average temperature profile recorded by thin probes in the central region of fruits and the temperature of purées obtained after atmospheric or vacuum pulping. A simulation of the blanching operation by COMSOL Multiphysics shows a relatively good agreement with the experimental results during steam blanching. The difference between the observed and calculated results may be due to the difficulty of placing the tip of the probe at the center of the fruit. Nonetheless, in these conditions, for the holding times tested, thermal equilibrium was not reached, and the temperature profile was not homogeneous along the cross-section of the fruit (Fig. 4-2b). After the rapid opening of the valve and the release of the pressure, the fruits burst, and the temperature of the homogenized mash obtained after vacuum pulping reached a temperature below 35 °C for the 30 and 40 s holding times.

When the flash explosion was not implemented and the blanched fruits were sieved directly at atmospheric pressure, an increase in the temperature of the purées obtained was observed because of the homogenization effect (Fig. 4-2a), and the final purée remained relatively hot for several minutes before cooling. At 50 s of holding time during steam blanching, no cooling was observed after FVE. Under these conditions, the fruits appeared totally destructured and stunted without turgidity because much liquid had flowed out, probably limiting the cooling effect of flash expansion.

According to Allaf et al. 2014 from a thermodynamic point of view, during the rapid release of pressure, water vapor from the fruit was instantly directed in the direction of the suction of the vacuum pump, thus losing a degree of freedom of movement. During this transient period, the velocity vectors of the particles were reduced into a two-dimensional space, which significantly improved the expansion rate and therefore the vaporization and cooling rates. As this occurs without an exchange of energy with the external environment, during this transient period, the diffusion of heat and matter did not respect the classic transfer laws that prevail when the state of matter is quasi-static (Allaf & Allaf, 2014). Therefore, during the FVE process, the temperature profile tended to approach high temperature short-term treatment (HTST), even though the temperature gradient inside the fruit remained high, with a relatively cold zone at the heart of the fruit (Fig. 4-2b).

4.4.1 Microbiological quality of fruit purée obtained by FVE treatment

The results of the microbiological analysis are presented in Table 4-1. Goldenberry discarded from the export chain usually has a microbial load less than 3 log CFU/g for aerobic mesophilic bacteria, molds and yeasts (Experiment 1, Table 4-2). The 30 s steam blanching only (SB 30 s) had a poor effect on reducing microbial load, whereas FVE carried out under the same conditions (FVE 30 s) made it possible to obtain completely

decontaminated purées. It should be noted that for steam blanching only, there was no rapid temperature drop, as shown in Figure 2a; therefore, for the same holding time, the decontamination efficiency was expected to be higher for SB than for FVE treatment. However, this was not observed since the experimental results repeatedly showed an enhanced effect of the coupling of steam blanching and FVE on the reduction of the microbiological load despite rapid cooling and the presence of a “cold zone” at the heart of the fruit. Similar results were observed when applying the FVE process to other food products (Mounir et al, 2014). It is hypothesized by some authors that the rapid release of pressure and the increase rate of self-vaporization of water vapor may cause cell membrane rupture and irreversible protein denaturation (Mounir et al, 2014); they were also able to show this damage on scanning electron microscope (SEM) images of affected microbial cells. To estimate the maximum logarithmic reduction that can be achieved by the FVE process, gooseberry fruits were allowed to spoil for several days at room temperature to reach a very high microbial load (Experiment 2, Table 4-1). Application of FVE to these fruits, with steam blanching for 30 s, showed minimum logarithmic reductions of 6, 9 and 7 log CFU/g for aerobic mesophilic bacteria, molds and yeasts, and fecal and total coliforms, respectively. Conversely, a very low reduction was achieved for only steam bleaching of 30 s (SB 30 s).

Table 4-1. Viability of aerobic mesophilic bacteria, molds and yeasts, and fecal and total coliforms in *Physalis peruviana* fruit purées.

Experiment 1	Plate microbial content (CFU/g)		
	Aerobic mesophilic bacteria	**Molds and yeasts**	**Fecal and total coliforms**
Experiment 1			
Initial count in fruits discarded from export market	2.53×10^2 (±10.41)	1.43×10^2 (± 6.23)	<10 (± 0)
SB 30s	3.8×10^1 (± 6.08)	6.0×10^1 (± 2.0)	<10 (± 0)
SB 40s	<10 (± 0)	<10 (± 0)	<10 (± 0)
SB 50s	<10 (± 0)	<10 (± 0)	<10 (± 0)
FVE 30s	<10 (± 0)	<10 (± 0)	<10 (± 0)
FVE 40s	<10 (± 0)	<10 (± 0)	<10 (± 0)
FVE 50s	<10 (± 0)	<10 (± 0)	<10 (± 0)
Experiment 2 Initial count on spoiled fruits	1.15×10^6 (±6.36)	1.61×10^9 (± 5.65)	9.0×10^6 (± 3.00)
SB 30s	9.7×10^5 (± 3.66)	8.1×10^8 (± 5.65)	8.6×10^6 (± 2.56)
FVE 30s	<10 (± 0)	<10 (± 0)	<10 (± 0)

Mean ± standard error, n = 3**.** SB: steam blanching; FVE: flash vacuum expansion. CFU: Colony forming units. Experiment 357 1: Steam blanching (30, 40, and 50 s/130 kPa) with and without the application of flash-vacuum expansion (5 ± 1.2 kPa). 358 Experiment 2: logarithmic reduction of a batch of fruit at a high level of contamination and processed by heating (30 s with 359 and without flash explosion).

4.4.2 Physicochemical characterization of purée

As seen in Table 4-2, steam blanching alone (SB) and the FVE process significantly increased the purée production yield by a range of 15-28% compared to the nonthermally treated mash. There were no significant differences found between SB and FVE. Heat

treatments soften tissues and facilitate the subsequent separation of seeds and larger fragments by sieving. A noticeable effect of the FVE process on the yield has been observed for other fruits where part of the skin was incorporated into the final puree after bursting, as in the case of purple passion fruit or grapes (Arias et al., 2022), (Brat et al., 2001). The steam blanching and FVE processes slightly increased the pH and decreased the TSS compared to the untreated purée (UP) (Table 4-3). However, when comparing SB to FVE, the differences in TSS were higher for blanching holding times greater than 40 s. Most likely, the bursting of the skin and tissues around the seeds solubilized some insoluble compounds that had been trapped by cell-wall polysaccharides. As shown in Figure 4-2b, the skin reached the highest temperature and was therefore more likely to burst into small particles.

The color coordinates of fruit purées were affected unevenly by the SB and FVE processes according to holding time. For all treatments, ΔE* was greater than 5, indicating a visually significant difference (Wu & Sun, 2013) compared to unpasteurized mash (UP). However, contrary to the classic thermal treatments, ΔE* was not due to an increase in the browning index (BI), as shown in Table 4-2, but to an increase in the positive chromatic component b*, which represents yellowness. These changes could be attributed to the destructuring of chromoplasts and better extraction of carotenoids from the skin to the mash.

Table 4-2. Effect of steam blanching (SB) and flash-vacuum explosion (FVE) flash processes on the physicochemical variables of sieved goldenberry purées.

	Steam blanching (Holding time in second)			FVE (SB Holding time in second)			UP
Variables	**30**	**40**	**50**	**30**	**40**	**50**	
pH	3.81±0.14a	3.84±0.07a	3.83±0.10a	3.83±0.08a	3.86±0.07a	3.92±0.10a	3.57±0.12^{b}
Yield (% w/w)[1]	67.73±0.032^{a}	65.47± 0.04^{a}	73.03±0.03^{a}	70.00± 0.03^{a}	68.25±0.07^{a}	70.75±0.03^{a}	56.78±0.04^{b}
L*[2]	55.82±1.52^{a}	55.81± 0.35^{a}	51.78±0.67^{b}	52.39 ±0.24^{bc}	52.24±0.44^{b}	53.17±0.28 ^{b}	51.22±0.8^{c}
a*[2]	25.16±1.17^{bc}	25.46 ±0.44^{b}	21.70±0.35^{e}	23.96± 0.31^{cd}	24.42±0.24^{b}	23.42±1.09^{d}	28.45±0.78^{a}
b*[2]	70.22±1.55^{a}	69.94±1.44^{a}	65.23± 0.96^{c}	65.74± 0.549^{c}	65.35± 1.31^{c}	67.99±1.42^{b}	62.73±1.08^{d}
ΔE*	9.53±1.52a	9.08±0.95a	7.32±0.32b	5.67±0.52c	4.93±0.51c	7.64±0.98b	
BI[3]	30.53±0.61bc	30.88±0.15bc	28.57±0.11b	30.95±0.34bc	31.57±0.43b	29.92±1.28c	36.88±0.22a
SS[4] (gxL^{-1})	12.35±0.47^{b}	12.20± 0.59^{b}	10.95±0.59^{c}	12.82 ±0.476^{ab}	13.10±1.22^{ab}	12.85±0.34^{ab}	14.00±0.15^{a}

Mean ± standard error, n=3, different letters in each row indicate that there is a statistically significant difference ($p < 0.05$). [1] w/w: weight/ weight. [2]Color coordinates in the CIELAB space: L*: luminance, i.e., lightness [0-100], a*: >0: red, <0: green, b*:>0: yellow, <0: blue. [3]BI=Browning Index. [4]Soluble solids. FVE: flash-vacuum expansion, UP: Untreated Purée.

Figure 4-3 shows that there was a significant effect of steam blanching holding times during the FVE process on the β-carotene content. Heating times of 40 s and the application of vacuum led to a higher content of β-carotene compared to the other process treatments and inclusively UP. The 40 s treatment with FVE was able to extract carotenoids from the skin of goldenberry, which is richer in carotenoids, as shown by (Etzbach et al., 2018).

In addition, the values for treatments at 30 s (SB and FVE) and 40 s (SB) did not show differences with respect to the content of carotenoids found in UP (Figure 4-3), indicating that under these conditions, the measurable content of β-carotene in the fruit remained stable. For a short holding time, β-carotene from goldenberry is quite heat stable (Olivares-Tenorio et al., 2017), nonetheless, at 50 s, the content of carotenoids was negatively impacted due to the higher temperature reached since protein denaturation and cell wall rupture exposed carotenoids to isomerization and epoxidation reactions (A. Oliveira et al., 2012). The results obtained for treatments at 50 s were similar to those reported by Castro et al., (2008) for goldenberry dehydrated with hot air at 60°C for various hours (Castro et al., 2008).

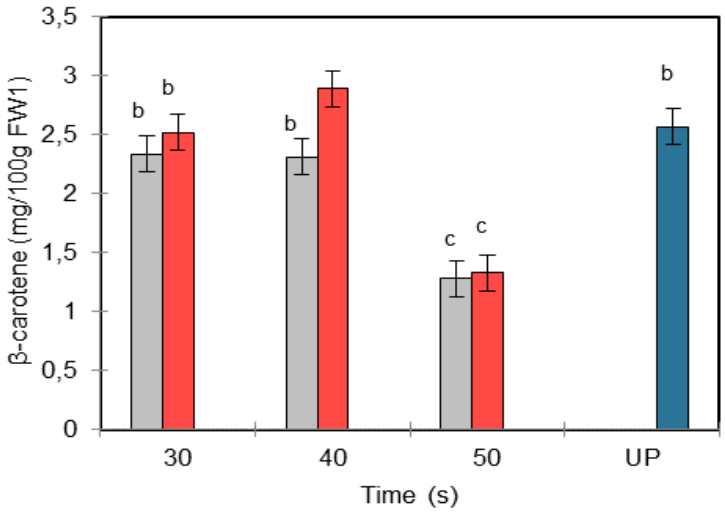


Figure 4-3. β-carotene Content in goldenberry purées obtained by steam blanching (grey bars) and flash-vacuum expansion (red bars). UP (blue bar): untreated purée. 1FW: fresh weight.

Figure 4-4 shows the effects of SB and FVE on a highly thermolabile compound, ascorbic acid (AA). The AA content (approximately 45 mg.100 g^{-1} FW) in the untreated sample (UP) was similar to that reported by Olivares-Tenorio et al., (2017) (Olivares-Tenorio et al., 2017). Figure 4 shows a greater negative impact ($p < 0.05$) when only steam blanching was applied compared to the FVE process for blanching holding times of 30 and 40 s. Indeed, Figure 2a shows that the fruit purees obtained after steam blanching and sieving at atmospheric pressure remained hot longer, whereas the addition of the FVE process induced rapid cooling, which better preserved the thermally labile ascorbic acid. Loss of AA in FVE purées with holding times of 30 and 40 s was relatively low (between 4-12%) with respect to blanching alone under the same conditions (approximately 30%). A similar reduction of 30% of AA has been reported for conventionally pasteurized goldenberry juice, (Ordóñez-Santos et al., 2017; Olivares-Tenorio et al., 2017). For 50 s blanching, a more drastic reduction (-66%) was observed, which was similar for SB and FVE, and this

observation was consistent with the mash temperature history shown in Figure 4-2a. The AA content was indeed a good indicator of the temperature history of the product and confirmed the impact of rapid cooling after pressure release below 40 s of steam blanching, proving again that the vacuum flash explosion (VFE) process under these conditions better preserves thermolabile compounds. Additionally, partial vacuum during pulping prevents the oxidation and loss of bioactive compounds (Brat et al., 2001).

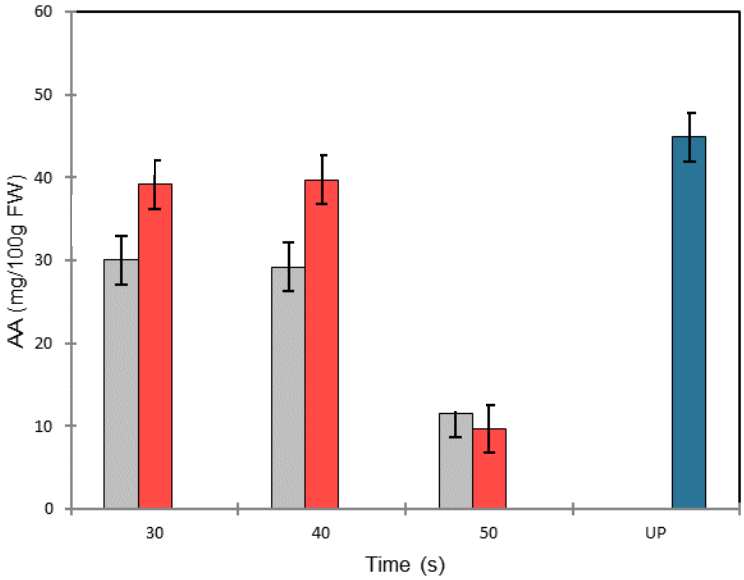


Figure 4-4. Ascorbic acid content in goldenberry purées obtained by steam blanching (grey bars) and flash-vacuum expansion (red bars). UP (blue bar): untreated purée. 1FW: fresh weight.

4.4.3 Effect of FVE on shelf-life quality of purée

The impact of FVE on the microbiological and physicochemical quality, a blanching holding time of 40 s was selected to assess the shelf-life quality of the purées produced. The goldenberry puree (FVE 40 s) was packaged following an "ultra clean" method directly at the outlet of the FVE system in irradiated multilayer aluminum bags and stored. The bioactive compounds AA and β-carotene were chosen as indicators to monitor the deterioration of FVE purées during storage at temperatures of 4 °C and 20 °C. The degradation of AA and β-carotene followed first-order kinetics, and the corresponding kinetic parameters (k, t1/2) are presented in Table 4. The values found for the parameter k were quite similar to pasteurized purees used for infant foods stored at 25 °C (Bosch et al., 2013). During the storage of goldenberry purée at 4 °C, there was a 12% decrease in the AA content at 30 days. After 45 days of storage, the reduction in the AA content was 80%, and after 60 days, the content remained below 10 mg.100 g-1 (Figure 4-4). At 4 °C, the half-life of AA was much longer (t1/2= 86 days) compared to storage at 20 °C (50 d). For a storage temperature of 20 °C, the reduction in AA content was much more drastic, implying that fruit purees must be kept at refrigeration temperature not for microbial reasons but for nutritional quality reasons.

For β-carotene, the half-life found was 14 days for storage at 20 °C, while when using refrigeration temperatures, it was extended to 84 d. The increase in stability of β-carotene under refrigerated storage was very significant compared to that reported for pasteurized goldenberry juice stored at 4 °C (57 d) (Gutiérrez Valencia et al., 2016). Reductions in β-carotene content of 38% and 51% were observed after 8 and 16 days of storage at 20 °C, respectively. After 60 days of storage at 4 °C, the residual content of carotenoids in the purée was approximately 40% of the initial content.

The results found in this study prove that the FVE process manages to produce purées with stability that is even higher than those reported for goldenberry extracts processed by pasteurization or HPP (Torres-Ossandón et al., 2018).

Table 4-3. Degradation kinetic parameters of ascorbic acid and β-carotene content of golden berry purée stored at 5 and 20 °C.

Compounds	Temperature (°C)	K (days−1)	R^2	$t_{1/2}$ (days)
Ascorbic Acid	20	0.139	0.85	50
	4	0.008	0.92	86
β-carotene	20	0.049	0.88	14
	4	0.0083	0.85	84

The high stability was also reflected in the color of stored purées. Color changes were imperceptible (ΔE^*_{ab}<5) up to 60 days of storage at 4 °C. The main changes were presented in the b* coordinate (yellowness) and hue angle h_{ab} (Table 4-4), which decreased slightly. The browning index remained constant and slightly increased between 60 and 75 days.

Table 4-4. Color difference, chroma, and hue angle of the goldenberry purées during storage (4 °C).

Storage time at 4°C	ΔE^*_{ab}	$_{ab}$	h_{ab}[1]	BI[2]	b*[3]
0	-	69.04±0.24a	1.37±0.28ab	32.67±0.41bc	64.27±0.27a
30	2.53±0.65c	70.68±0.84a	1.40±0.03a	32.02±0.03c	65.91±0.88a
45	4.58±0.18b	65.07±0.23b	1.30±0.03b	30.29±0.38d	60.39±0.14b
60	4.23±0.71b	65.83±1.29b	1.13±0.02c	33.33±0.43b	60.40±1.08b
75	7.80±0.40a	63.31±0.33b	0.97±0.03d	36.54±0.61a	57.15±0.28c

Different letters in the same column indicate significant differences ($p < 0.05$); n=3. [1]Hue angle. [2]BI=Browning Index.[3]Color coordinates in the CIELAB space: b*:>0: yellow, <0: blue.

4.4.4 Analysis of energy consumption

The energy performance was estimated by analyzing the consumption of all the subsystems that make up the FVE process presented in Figure 4.-5. The process consumes electrical energy to power the liquid ring vacuum pump, the air compressor that moves the pneumatic valve actuator, the pulper and the chiller for the production of cold water. Additionally, there is a consumption of thermal energy related to the generation of

the steam required during the blanching of whole fruit. Thus, the total energy consumed during the FVE process is the sum of electrical power and thermal energy:

$$E_{Tot} = E_{electricity} + E_{steam} \quad \textbf{Eq. 4-9}$$

The electrical energy consumed E_k of each of the *k* subsystems of the above-mentioned equipment is given by:

$$E_k = \int_0^{t_{0,k}} \dot{W}_k dt \quad \textbf{Eq. 4-10}$$

Thermal energy required to produce the steam E_{steam} used in the direct steam injection system is given by:

$$E_{steam} = \frac{\dot{m}_{steam}\left(\int_{T_{ow}}^{T_v} C_p(T)dT + \Delta H_v\right)}{\eta} \quad \textbf{Eq. 4-11}$$

Thermal energy required for heating the fruit is given by:

$$Q = \frac{m_f C_{p_f} \Delta T}{t} \quad \textbf{Eq. 4-12}$$

Mass flow of steam required to heat the fruit is given by:

$$\dot{m}_{steam} = \frac{Q}{H_v} \quad \textbf{Eq. 4-13}$$

Finally, the specific energy consumption S_E is given by:

$$S_E = \frac{E_{Tot}}{m_p} \quad \textbf{Eq. 4-14}$$

Thus, solving Equations 4-9 to 4-14 yields an average specific consumption of 0.31 kWh/kg of final fruit purée. A total cycle time of 1.5 min was taken to process 1.5 kg of fresh fruit, giving an average mass throughput based on continuous processing of 64 kg of blanched whole fruit per hour, ultimately yielding 44 kg of processed mash per hour. The

average specific consumption value was calculated specifically for semi-industrial pilot equipment described elsewhere (Arias et al., 2022) and could probably be reduced at a larger scale production level, as some equipment may be oversized. Nonetheless, in these conditions, the most energy-intensive operation appeared to be the liquid ring pump followed by the boiler, with power intensities of 0.11 and 0.075 kwh.kg^{-1}, respectively.

Thus, the energy needs can be divided into thermal energy 0.075 kwh.kg^{-1}, which can be provided by fuel oil, gas, and biogas, among others, and 0.23 kwh.kg^{-1} in electrical energy, which can also be provided by renewable sources. The specific energy consumption during the FVE process is lower on average than most conventional processes used for fruit processing, estimated at approximately 1.1 kWh.kg^{-1}, including thermal and electrical energy (Ladha-Sabur et al., 2019). In addition, the FVE process is carried out in one single-step 5-unit operation corresponding to blanching, pulping, pasteurization, cooling and deaeration, which requires a full range of equipment during conventional processing.

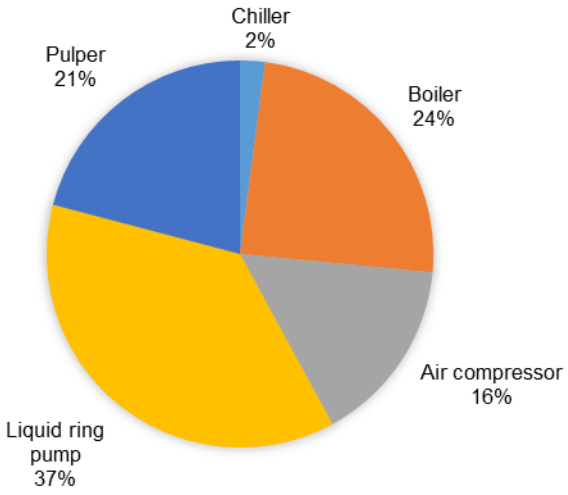


Figure 4-5. Distribution of energy consumption in Flash-vacuum expansion (FVE) process.

4.6 Conclusions

The study demonstrated that a very short steam blanching time (40 s) of whole fruits and the sudden application of vacuum, followed by vacuum sieving results in a high-quality goldenberry puree. The FVE process has been shown to have an increased effect on the decontamination of goldenberry puree with a microbial reduction of more than 6 log CFU/g. Based on quality indicators such as ascorbic acid and β-carotene, the shelf life of purees was 90 days. Indeed, this innovative processing technology makes it possible to meet food safety standards without compromising the stability of the bioactive compounds. The equipment costs and specific energy consumption of this technology are lower than those of conventional processes, and FVE can be easily coupled to an aseptic or

"ultraclean" packaging system, which makes this process highly viable for small and medium agro-industries, even in developing countries.

Declarations

Author contribution statement

Claudia Arias: Methodology, Formal analysis, Writing original draft. Pablo Rodríguez: Conceptualization, Methodology, Data curation, Formal analysis, Supervision, Project administration, Funding acquisition. Iris Soto: Methodology, Formal analysis, Writing—original draft. Rowan Vaillant: Methodology, Formal analysis of study of heat transfer and simulation. Misael Cortés: Methodology, Writing—review and editing**.** Fabrice Vaillant: Conceptualization, Methodology, Data curation, Formal analysis, Supervision, Funding acquisition.

Patents

Authors declare a patent related to the published work is in the protection process (Dispositivo para la producción de purés, nectares o extractos de material vegetal NC2021/0016741 Superintendencia de industria y comercio).

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Data availability statement

The data that has been used is confidential.

Declaration of interests statement

The authors declare no competing interest.

Additional information

No additional information is available for this paper.

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5. CONCLUSIONES Y RECOMENDACIONES

5.1 Conclusiones generales

- Los resultados mostraron que el proceso de FE permite el desarrollo de purés de uchuva y gulupa con calidad microbiológica, fisicoquímica, sensorial, con gran aceptación por los consumidores y una vida útil promedio de tres meses a temperatura de refrigeración comercial. Los productos desarrollados son por tanto escalables a condiciones comerciales ya que cumplen lo exigido por la normatividad colombiana para la elaboración de pulpas o purés de frutas

- El proceso FE permite la descontaminación de los purés de uchuva y gulupa y al mismo tiempo incorpora compuestos bioactivos de la cáscara, lo que les otorga una mejor textura y apariencia a los productos.

- Los costes y consumos específicos de energía de la tecnología FE son inferiores a los costes y consumos específicos de energía utilizada en los procesos convencionales, lo que hace que este proceso sea altamente viable para pequeñas y medianas agroindustrias.

- Con el desarrollo del proyecto, se proyectan beneficios sociales tales como la generación de empleos directos, la oportunidad de obtener mejores ingresos a los productores de uchuva y gulupa, satisfacer una necesidad del mercado y en general propiciar una mejor calidad de vida.

5.2 Recomendaciones

- Se recomienda evaluar un escalamiento a nivel industrial de los productos de innovación, obtenidos por la tecnología FE, (puré de uchuva y gulupa) para validar su eficacia a mayor escala y evaluar su viabilidad financieramente.

- Se recomienda acoplar envasadora aséptica al proceso de FE, con el propósito de alargar la vida útil de los productos.

- El equipo de proceso es un piloto y por tanto se recomienda incorporar sistemas de alimentación automatizada, inclusión de más refinadoras y métodos de control de variables automatizados todo ello para elevar la eficiencia de operación.

- Se requiere la transferencia de la tecnología de FE a entornos productivos y el acompañamiento del posicionamiento de los productos innovadores por parte de la institucionalidad como ministerio de industria y comercio para conectar los productos de la mejor manera ya que las asociaciones tienen un foco de producción y no son

fuertes en temas de comercialización y posicionamiento de procesos y productos de base tecnológica.

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7. ANEXO 1

Artículo: "**Innovative Process Coupling Short Steam Blanching with Vacuum Flash-Expansion Produces in One Single Stage High-Quality Purple Passion Fruit Smoothies": https://doi.org/10.3390/foods11060832**; publicado en la:

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Artículo: “**FLASH-VACUUM EXPANSION, A LOW COST AND ENERGY-EFFICIENT ALTERNATIVE PROCESS TO PRODUCE HIGH QUALITY FRUIT PUREE: APPLICATION TO *Physalis peruviana* L**”: https://doi.org/10.1016/j.heliyon.2023.e16969; publicado en la:

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