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Spent Hemp as an Animal Feed and Vertical Price Transmission in US Hemp Value-Added Supply Chain

Solomon E. Odiase
University of Kentucky, odiasesolomon@gmail.com
Author ORCID Identifier:
https://orcid.org/0000-0001-9407-2491
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Solomon E. Odiase, Student

Dr. Tyler Mark, Major Professor

Dr. Tyler Mark, Director of Graduate Studies

SPENT HEMP AS AN ANIMAL FEED AND VERTICAL PRICE TRANSMISSION IN US HEMP VALUE-ADDED SUPPLY CHAIN

THESIS

A thesis submitted in partial fulfillment of the
requirements for the degree of Master of Science in the
College of Agriculture, Food and Environment
at the University of Kentucky

By
Solomon E. Odiase
Lexington, Kentucky
Director: Dr. Tyler Mark, Professor of Agricultural Economics
Lexington, Kentucky
2022

https://orcid.org/0000-0001-9407-2491

ABSTRACT OF THESIS

SPENT HEMP AS AN ANIMAL FEED AND VERTICAL PRICE TRANSMISSION IN US HEMP VALUE-ADDED SUPPLY CHAIN

This thesis comprises of two articles covering spent hemp's prospects as an animal feed and the price interaction across the hemp commodity value-added supply chain. The first article uses a comparative analysis tool to analyze the potential of spent hemp as an animal feed or feed ingredient based on its yield, nutritional composition and market price. This comparative advantage analysis revealed that spent hemp is competitive based on its rich essential nutritional content, comparatively high yield per acre, and low market price. Furthermore, with the increasing drought conditions, production cost and market price of alfalfa hay, spent hemp may fill in as a supplement or alternative that could bridge the forage hay gap in the US animal feed industry. The second article employs an autoregressive distributed lag, investigates the price relationship across three stages of the hemp value chain, and applies the error correction model to determine the response of different stages in the value chain in the event of market turbulence. The result of this model suggests that hemp biomass and crude cannabidiol (CBD) oil prices adjusted symmetrically with each other while the refined cannabidiol hemp oil adjusted asymmetrically with the incidence of negative shocks in other phases of the value chain. This implies that the refined cannabidiol (CBD) hemp oil market price is more stable in the incidence of unpleasant shock along the hemp value-added supply chain.

KEYWORDS: Spent Hemp, Hemp Nutritional Content, Value-Added Supply Chain, Vertical Price Transmission, Autoregressive Distributed Lag, Hemp Biomass

Solomon E. Odiase

(Name of Student)

11/18/2022

Date

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By

Solomon E. Odiase

Dr. Tyler Mark

Director of Thesis

Dr. Tyler Mark

Director of Graduate Studies

11/18/2022

Date

DEDICATION

To my late mum, Francisca Nneka ODIASE.

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CHAPTER 1. INTRODUCTION

The US hemp market is new and volatile with a research and development deficit of over half a century. It is an intriguing research niche, given that there is a considerable gap in knowledge about industrial hemp's economic importance and prospects.

The first article envisioned the potential prospect of spent hemp as an animal feed. Before the strict restriction and eventually a ban on the production and processing of hemp, hemp was an intervention fiber crop that sustained the fiber-based products demand of the US populace during the period of the second world war until the restoration of the cheaper fiber substitutes supply chain after the war in 1945. The article analyzed the potential of hemp biomass byproduct as an animal hay to bridge the animal hay gap and influence a market boom in the hemp industry. To ascertain the possibility of spent hemp to catalyze hemp market growth, a comparative analysis of the nutritional composition, yield and market price of each forage hay (spent hemp, and other hay substitutes – grass hay and legume hay, alfalfa, also known as the "Queen in the South" because of its rich nutritional composition and its ability to fix nitrogen to the soil) was performed. The outcome of this research showed that hemp nutritional value compared favorably with the "Queen in the South" hay. Also, hemp yield per acre is similar to the grass and alfalfa yield (measured in tons). Alfalfa and grasses are perennial crops that can be grazed directly by livestock. They can survive and reproduce for over two years unlike hemp which is an annual crop that cannot be grazed directly by livestock until the extraction of the cannabidiol (CBD) and tetrahydrocannabinol (THC) content. It is important to highlight that while this may seem like a limitation for hemp in this comparison, one should keep in mind that spent hemp (extracted hemp biomass) is the byproduct of cannabidiol (CBD) production. Spent hemp if approved as an animal feed will be a secondary source of revenue and the CBD rich floral value covers for the additional costs of replanting the field. This leads to the last indices of comparison, market price. Spent hemp is a potentially the most cost effective despite its high nutritional composition because of the stigma surrounding the CBD residuals in the extracted hemp biomass. If legalized as an animal feed, this speculated price advantage will be savored by the early spent hemp feed adopters until the demand reaches equilibrium with the supply.

The second article studied the price interaction among the agents in the hemp value-added supply chain in the United States. The agents in this supply chain include the producers of the primary products (hemp biomass), the processors (Processor I) of the intermediary product (crude CBD hemp oil) and the processors (Processor II) of the final products (refined CBD hemp oil). The research article investigated the effects of exogenous shocks on the behavior of price across the agents at different stages of the value chain with the core objective of understanding how the impact of a price change at each phase of the value-added chain affects other phases. An Autoregressive Distributed Lag Error Correction model was employed to evaluate the co-integration among the time series price and determine the speed of price adjustment at different phases in the hemp value chain with the interference of an external shock. The result showed the effect of an exogenous shock causing a deviation in the long-run equilibrium is corrected at an approximated symmetrical and significantly quicker speed by the first and second agents in the supply chain. Unlike the first two agents, deviation from long-run equilibrium is adjusted at an insignificant speed by the third agent in the value chain. One possible explanation is that the advantage of creating premium value through value addition gives processor II an edge to retain a fairly more stable price and explore more profit even the in the face of negative interference in the market. As mentioned at the beginning of this chapter, the hemp market is new and volatile, with numerous new investors. Understanding the market price interaction is necessary for investors to make better investment decisions and, ultimately, stand a higher chance of earning positive net returns on their investments.

CHAPTER 2. Spent Hemp as an Animal Feed: A Potential Catalyst for Market Boom for Industrial Hemp Industry in The United States

2.1 Abstract

After over fifty years of a ban on hemp, the United States has once again legalized industrial hemp production. Before the strict restriction and subsequent prohibition of hemp cultivation and processing in the US instigated by public health concerns for the consumption of *Cannabis Sativa*, hemp plant was a major source of fiber. Hemp was the raw material that meet the fiber demands of the US cordage industry to make textiles, bioplastics and ropes for the populace when the second world war (WWII) disrupted the cheap abaca and jute fiber supply chain. This article analyzed the prospects of hemp as a forage alternative for hay production and/or as a component of animal feed ingredients by comparing its nutritional composition and market price with the undisputed forage hay giant – alfalfa, and grass hay. This comparative advantage analysis revealed that hemp is competitive based on its rich essential nutritional content, comparatively high yield per acre, and market price. With the increasing drought and the production cost and market price of alfalfa hay, hemp forage may fill in as a hay supplement or alternative that could bridge the forage gap in the US animal feed industry.

2.2 Introduction

Hemp, often referred to as "industrial hemp" is an agricultural commodity often confused with marijuana by the public (1). Both plants are from the same genus and epithet known as *Cannabis Sativa* but from different cultivars. Several articles have defined the economic importance of hemp and highlighted the similarities and differences between industrial hemp and marijuana (2-4). Industrial hemp and marijuana are plants that have genetically distinct forms of cannabis but differ in their use, chemical composition, and cultivation practices (5). Industrial hemp plant on a dry weight basis has delta-9 tetrahydrocannabinol (THC) content, a psychoactive compound of 0.3 percent or less which implies that an individual cannot get high or intoxicated when they consume hemp or hemp-based products. In contrast, marijuana has no threshold on THC level (1, 6).

The industrial hemp plant is comprised of stalk, seeds, roots, leaves, and flowers. Each component of the plant has associated economic importance (7, 8, 9).

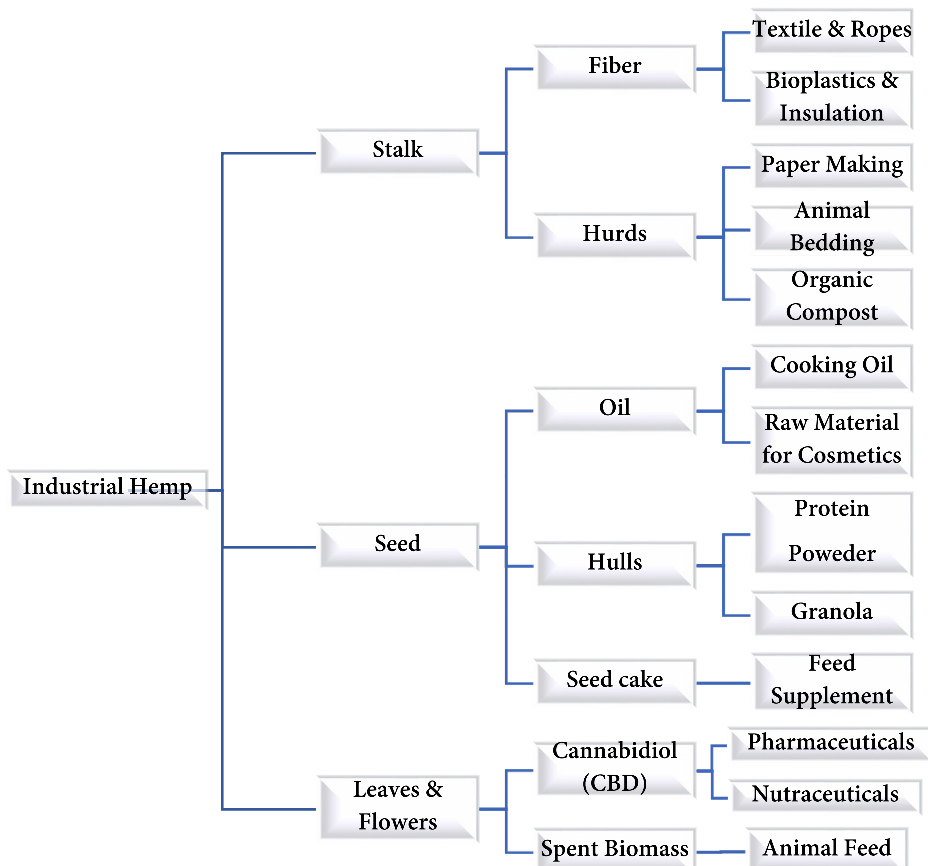

Figure 2-1 Economics Importance of different parts of *Cannabis sativa* (Hemp)

New Leaf Data Service (NDLS) defined hemp biomass as dried hemp material comprised of stalks, leaves, flowers, buds and/or seeds. The byproduct of the milled, grounded, pelleted or baled hemp biomass after extraction of its cannabinoid or cannabigerol content is a potential source of hay to supplement alfalfa and grass forage which are presently widely grown forage for livestock hay production. The alfalfa forage is significantly plagued by drought and depleting Ogallala aquifer; an essential source of moisture for agricultural production, leading to an undersupply of hay to meet the farm demand and growing cost of livestock hay (10).

According to ERS, "As of March 8, 2022, drought conditions were most severe in Texas, Oklahoma, Oregon, Nevada, Utah, Montana, and New Mexico. The United States Drought Monitor (USDM) recorded that at least 20 percent of Western states' land was classified as experiencing extreme drought. Data reported by the USDM demonstrated that the incidence of drought in the Western US during the summer of 2021 exceeded all past droughts in the region since 2000" (11).

The National Drought Mitigation Center (NDMC, 2022) also reported that over 10 percent of alfalfa hay acreage in the United States was affected by the drought condition and recorded the effect of this unprecedented drought on the alfalfa production acreage as the most severe in the last decade. Given that alfalfa forage is an essential component of animal hay, and its production is predominantly concentrated in the region of historically severe drought conditions, there is a high probability for significant yield reduction, which may impact animal feed prices negatively (12). Although presently restricted by government regulation, the adoption of spent hemp as an alternative source of animal feed could be a potential solution to bridging the hay supply gap and the rising cost of animal hay.

2.3 History of Hemp

Most authors believe that hemp originated from China (13, 14) and was initially cultivated for fiber, fuel, food, and oil. However, the hemp plant distribution boom started in Europe in the sixteen century. The plant was renowned for its cordage use and medicinal properties. Hence, it was named *Cannabis Sativa* by Discorides in 1537.

The plant was unpopular in the United States until 1645, when the Puritans from New England propagated the plant in the US as a source of fiber. The hemp plant cultivation spread to Virginia and Pennsylvania before the American Revolution, which started in 1765. In 1775, Hemp was introduced to Kentucky by migrants from Virginia. The plant's favorable adaptation in Kentucky led to the development of the cordage industry in Kentucky (15). Between 1840 and 1860, the hemp industry flourished in Kentucky, Missouri and Illinois due to high demand volume for cordage and sailcloth, given the plant's strong and rot-resistant fiber properties. However, the growth of the hemp fiber industry was trumped by the development of the cotton gin which led to increased cotton production. In addition, importing cost-effective substitute fiber crops such as jute and abaca gradually displaced domestic hemp. In response to World War I, the demand and production of hemp slightly increased, and fiber hemp was grown in several states, including Kentucky, Wisconsin, California, North Dakota, South Dakota, Minnesota, Indiana, Illinois, Ohio, Michigan, Kansas, and Iowa (16).

The increasing public health concerns for cannabis consumption facilitated the Marijuana Tax Act, passed in 1937 by the US government, placing all Cannabis production under the regulation of the Treasury Department. In addition, the Marijuana Tax Act imposed tax on *Cannabis sativa* and required the federal government's registration and licensing of all hemp growers to curb the production of psychoactive cannabis plants in the United States. Also, penalties were established for lawbreakers who engage in producing, selling, or possessing marijuana (16).

The disruption of jute and abaca supplies from the tropics to the US was caused by the second world war. To bridge the supply chain gap, an emergency hemp program was adopted to develop hemp as a domestically produced fiber substitute for the cordage industry. The program boosted the local hemp production industry. By 1943 and 1944, hemp produced in the US reached its peak production volume, then fell precipitously after the war in 1945 as legal restrictions on production were tightened back and supplies of lower cost tropical fibers were restored (17).

In 1970, the Controlled Substance Act (CSA), which required that the production, importation, possession, utilization, and distribution of certain substances were regulated, was signed into law by President Richard Nixon. Under this Act, drugs and certain chemicals substances used in the manufacture of drugs were classified into five (5) schedules based on the drug's acceptable medical use and the drug's potential for abuse or chronic dependency. Schedule (I) and schedule (IV) indicating substance with highest and lowest potential for abuse, respectively. The CSA categorized any variety of cannabis (industrial hemp included) as a schedule (I) substance that was illegal to be grown without a permit from the Drug Enforcement Agency (DEA) in the United States (18). The requirements to obtain a permit from DEA to grow industrial hemp was cost prohibitive. Hence, the demand for industrial hemp was met by importing from hemp-producing countries: Canada, Europe, and China (19).

The period between 2014 and 2018 can be described as the breakthrough period for hemp. The paradigm shift started with the implementation of the 2014 Farm Bill known as the Agricultural Improvement Act of 2014. The Act relaxed hemp production and marketing restrictions in the United States and allowed research institutions and the Departments of Agriculture to grow industrial hemp should their local state laws authorize it. The 2014 Farm Bill was modified in the 2018 Farm Bill known as the Agriculture Improvement Act of 2018 which further relaxed the limitations in the previous Farm Bill. As a result, individuals and businesses could obtain licenses to grow hemp for commercial purposes, legally transport hemp biomass throughout the United States, and have access to low crop insurance costs (20, 21).

2.4 Research Objective and Methodology

The core objective of this research is to analyze the potential impact of spent hemp as an animal feed to the livestock industry and its effects on the hemp market.

To conduct a critical analysis and reach an objective conclusion, the scope of this research employed a comparative analysis tool to compare industrial spent hemp with other forage hay substitutes. The comparative advantage of spent hemp among other forage hay will be established. Also, the potential impact of spent hemp inclusiveness in animal feed to bridge the animal hay supply gap and its effect on the hemp market was analyzed. The indices used in the comparative analysis in the research included the following:

i. Yield and productivity per acre

ii. Nutritional composition

iii. Market price trend of spent hemp and a predominantly grown legume and grass forage.

2.5 Spent hemp as an animal feed – 'Spent Hemp versus Alfalfa and Grass forage hay'

Spent hemp was compared with legume hay (alfalfa) and grass hay (timothy), which are highly grown animal forage crops in the United States, based on their nutritional content, productivity per acre and market price

2.5.1 Productivity and Yield per acre

Alfalfa, a perennial forage legume, has earned the title "The Queen of the Forages" because of the plant's abundant protein content and its potential to yield high forage even without the artificial addition of nitrogen to the soil. It has an optimum productive life span of 3-5 years and a production yield of 6000 to 12000 pounds per acre i.e., a 3 to 6 tons equivalent (22, 23). Alfalfa fields can be harvested up to 4 times annually. Some of the commonly grown grasses in the US are timothy, orchard grass, oat, triticale (rye and wheat hybrid), and fescue grass (24). The average grass yield across about three cuttings is estimated at 5 tons per acre.

Industrial hemp, an annual crop with a varying yield of 3 to 6 tons per acre, compare favorably with alfalfa and grass yield but unlike other forages, animals cannot graze the plant directly on the field because of its cannabidiol and tetrahydrocannabinol content. Hemp plant is primarily propagated for its CBD and fiber and the extracted hemp biomass is a byproduct of high nutritive value that can serve as hay for livestock consumption. Unlike alfalfa and grass, hemp plant productivity and quality are not affected by weed. Hemp plant has a morphological advantage to compete and suppress weeds. The plant's height ranges from 4 to 15 feet depending on the cultivar and agronomic practice employed by the farmer (5). This feature enables the plant to compete for sunlight and the leaves forming canopies to deprive weeds of sunlight (25).

2.5.2 Nutritional Composition

The major nutritional content of the plant analyzed to ascertain the quality of the forage are the Crude Protein (CP), Digestible Dry Matter (DDM), Dry Matter Intake (DMI), Acid Detergent Fiber (ADF), Neutral Detergent Fiber (NDF), Total Digestible Nutrients, and Relative Feeding Value (RFV). Table 2.1 show the quality standard for categorizing different forage hay.

Table 2-1 Quality Standards for Legume, Grass, or Grass-Legume Hay

Quality Standard	CP	ADF	NDF	DDM	DMI	RFV
Prime	>19	<31	<40	>65	>30	>151
1	17 – 19	31 – 35	40 – 46	62 – 65	3.0 – 2.6	151 – 125
2	14 – 19	36 – 40	47 – 53	58 – 61	2.5 – 2.3	124 – 103
3	11 – 13	41 – 42	54 – 60	56 – 57	2.2 – 2.0	102 – 87
4	8 – 10	43 – 45	54 – 60	56 – 57	2.2 – 2.0	102 – 87
5	<8	>45	>65	<53	<1.8	<75

Source: Hay Market Task Force, American Forage and Grassland Council.

Table 2-2 Nutritional Content of Hemp Forage and Forage Substites

Nutrient	Hemp (whole)	Hemp (Leaf and Flower	Hemp (Spent Flower)	Alfalfa Hay	Alfalfa (Dried)	Alfalfa (Pellets)	Grass Hay (Timothy)
Avg. Dry Matter	70	93	97	89.4	90.6	92	27
Avg. Crude Protein	7	21	23	18.2	18.3	18	13.8
Avg. Crude Fat	3	9	6	2.1	2.7	2.9	2.2
Avg. Total Digestible Nutrients (%)	24	68	68	54	55	56	59
Avg. Neutral Detergent Fiber (%)	53	45	20	44.8	45	40.9	62.2
Avg. Acid Detergent Fiber (%)	40	21	14	33.4	34	32.2	34.2
Relative Feed Value	101	151	371	131	129	145	93

Source: PanXchange Hemp and Animal Feed Industry Report

Table 2-3 Nutritional concentration of hemp plants, hemp flowers, seeds, hulls, and spent flower

Nutrient	Hemp (whole)	Leaves	Stalk	Flower	Seed	Hull	Spent flower
DDM	70.3	88.9	64.8	90.9	89.8	92.9	96.6
CP	6.9	13.0	5.3	21.2	23.0	20	24.5
CF	2.7	8.9	1.2	12.5	13.2	4.6	3.2
TDN	24	41	19.8	53.6	61.5	54.3	46.0
NDF	81.6	44.7	84.4	52.5	53.2	27.9	30.9
ADF	60.8	20.8	64.6	26.1	29.6	18.0	18.1
Calcium	1.4	4.3	1.0	2.3	2.6	5.7	3.6
Phosphorus	0.3	0.4	0.3	1.1	0.7	0.4	0.4
Potassium	1.1	3.3	0.9	2.4	1.3	1.9	2.4

Source: Nutrition concentrations of industrial hemp plant components

Table 2-2 and 2-3 shows the nutritional content of different components of hemp, legumes, and grass forages (10, 26). Dry matter measures the amount of moisture in the hay. The water content of hay is preferably less than or equal to 10 percent and a dry matter content of about 90 percent. Crude Protein indicates amino acids and nitrogen content level in the forage. The Acid Detergent Fiber and Neutral Detergent Fiber account for the poorly digestible and cumulative fiber content in the forage. A lower level of ADF (<31) and NDF (<40) is preferable. The ADF is correlated with the DDM which implies that the lower the ADF content of the feed, the higher the digestibility of the feed's dry matter. The NDF content has a negative relationship with the DDI. Thus, the lower the NDF content, the higher the dry matter intake. The Relative Feed Value of the feed is determined by the ADF and NDF content in forage. The RFV represents the quality, digestibility, and feed intake volume (palatability) of the animal feed. RFV is the most widely accepted criterion when choosing forage suitable for livestock ration (27-29).

Some of the core indices for measuring the nutritional composition of forage hay are indicated in Table 2-1. Alfalfa, which is the preferred forage because it has a high RFV within the range of 129 to 145 and a crude protein value ranging from 16% to 22%. Grass hay has a low RFV of 93, and 5% to 14% crude protein content. The percentage of crude protein varies depending on time of harvest. The crude protein content is highest in the vegetative stage and declines as the forage crop transitions into the flowering stage (23, 29).

Given that RFV and protein content are prime measures for grading the quality and market value of forages, alfalfa hay is unarguably a better forage than grass hay. This could further explain why alfalfa commands a higher market value than other forages.

Spent hemp's nutritional content is comparable with alfalfa legume, if not better. The whole hemp plant (hemp biomass) has a high percentage of NDF and ADF because of the high fiber content in the stalk. However, the spent hemp derived after the extraction of fibrous stalk, CBD and THC from hemp biomass for industrial use is the proposed source for animal hay. The nutritional content of the byproduct (spent hemp) is best estimated by the nutritional analysis of the spent leaves and flowers, which are low in poorly digestible dry matter (NDF and ADF) and high in digestible dry matter (TDN). The core advantage of spent hemp, if approved is the availability of spent hemp biomass and proximity to farms. The US has a large and widespread hemp industry that produces and processes the crop. Livestock farmers may be able to access spent hemp biomass from a close location, which is helpful for cutting down on transportation cost.

From a nutritional standpoint, spent hemp commands relevance, it has more protein content, a higher total digestible nutrient and a lower amount of poorly digestible nutrients. The spent hemp nutrient proportion scores the plant a higher RFV than alfalfa. Hence, based on nutrient composition of interest, spent hemp will be a potentially preferred hay, if approved for use as an animal feed.

In the feed trial research conducted by Oregon State University, the spent hemp fed livestock (cattle and sheep) performed well. However, the major limitation was that they consumed only 10 percent of their ration grudgingly because of the low feed palatability (30).

2.5.3 Market Price of Forage Hay

Forage with higher nutritional composition and quality has more value to the livestock farmer. This is because the farmer predominantly buys hay for its nutrient composition. Hence, the core determinant of the forage market value is the nutritional content's richness of the forage (27, 31). To simply put, the higher the nutrient in the forage, the higher the market price. In feed production, nutrient-rich hay requires lesser concentrates and minimizes the feed's cost. This could explain why alfalfa commands a higher market value than different grass forages. Given that the core metrics of the market value of hay is the quality and nutritional composition, the potential market value of hemp is expected to be similar with alfalfa market value. However, there is a probability of significant drop in market value because of the stereotypic stigma surrounding hemp consumption and the uncertainty of the outcome of feeding animals with spent hemp. The research speculates a >50 percent decrease in the market value of spent hemp as a result of this stigma and uncertainty of adopting spent hemp as an animal feed.

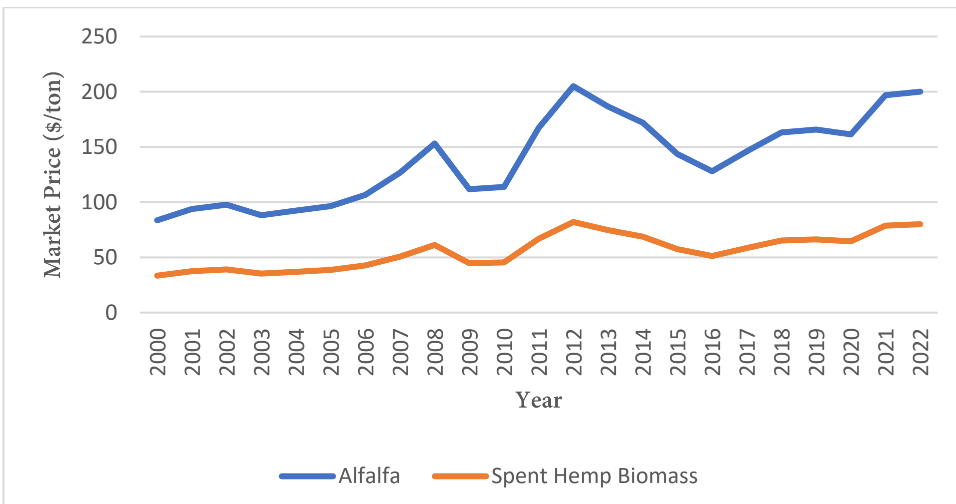

Figure 2-2 Avg. Alfalfa Price Trend in the US (NASS) and Avg. Price of Spent Hemp Biomass (Research Speculation)

2.6 Conclusion and Policy Implications

The present drought and continued deteriorating Ogallala aquifer, situated in the region of major alfalfa producing state, is potentially expected to reduce alfalfa productivity, increase production cost, and ultimately increase the market price of alfalfa hay. Based on the comparative indices: nutritional content, yield, and market price, spent hemp compare favorably with alfalfa legume and grass hay. Spent hemp, if approved as a feed ingredient, can be the alternative that met the need of the livestock farmers when the soil was plagued by depleting moisture and starved by rainfall. Hemp plant could once again be an intervention crop to bridge the animal feed gap in the US just like it did for the US cordage industry when the cheap abaca and jute fiber supply chain was disrupted by World War II. Suppose the extracted hemp biomass byproduct is authorized to be a source of hay or animal feed ingredient, hemp forage could gain market share in the animal feed industry which may contribute to an overall hemp market boom, and this could potentially influence the stock price of publicly traded hemp companies positively.

According to PanXchange CEO, Julie Lerner's explanation of the evolution of a commodity (32). The hemp industry is at the point where research and development of alternative uses to solve existing problems and boost demand for the commodity will influence the growth of the hemp commodity market. Increase in the demand for hemp-based products will aid in the establishment of a long-term hemp sustainable market (33). This innovation may not be adopted by every farmer at first, given the existing stereotypic stigma surrounding hemp consumption. However, until the US Food and Drug Administration make policies that will authorize hemp biomass byproduct as an animal feed intensive research, we may never know the limit of untapped potential in this innovation and could be underutilizing and wasting resources. The learnings from spent hemp livestock fed research will serve as a base for understanding the economic benefits of adopting spent hemp as an alternative source of animal feed. If the research is successful, it will educate farmers on the merits of adopting spent hemp and convince potential consumers that there is no health risk associated with the consumption of spent hemp fed livestock.

CHAPTER 3. VERTICAL PRICE TRANSMISSION IN THE US HEMP VALUE-ADDED SUPPLY CHAIN

3.1 Abstract

The US hemp market is a new, volatile, and intriguing research and development niche, given that there has been over half a century of research and development deficit. This research examined the effects of exogenous shock at each stage on other phases of the value-added supply chain – hemp biomass, crude cannabidiol hemp, and refined cannabidiol hemp oil. The research used the Augmented Dickey-Fuller (ADF) test to identify the stationarity nature of the time series data and employed the Autoregressive Distributed Lag (ARDL) to check the co-integration relationship among the variable time series. It also investigated the price adjustment speed after a deviation from long-run equilibrium caused by an exogenous shock using the ARDL Error Correction model. A pairwise Granger Causality test was conducted to determine which phases in the value chain significantly granger influence the other. The result of the research showed that hemp biomass and crude cannabidiol oil prices adjusted symmetrically with each other, while the refined cannabidiol hemp oil adjusted asymmetrically with the influence of negative shocks in other phases of the value chain. This implies that the refined cannabidiol hemp oil market price is significantly stable in the incidence of unpleasant shock along the hemp value-added supply chain.

3.2 Introduction

Prior to the prohibition of the act of cultivating industrial hemp (*Cannabis sativa*) over a half-century ago, the hemp plant was renowned for the economic importance of its fiber in the cordage industry (25). Hemp fiber was the solution to the fiber shortage when war (World War II) disrupted the US cheap and heavily imported abaca and jute fiber supply chain before its production declined significantly because of the legal restriction enacted on the production of hemp after the war and ultimately, the hemp production halted after hemp was banned in 1970 (17).

The legalization of industrial hemp in the Agricultural Improvement Act of 2018 (also referred to as the 2018 Farm Bill) signed into law by President Trump, removed hemp from the Controlled Substance Act (CSA) of 1970 enacted by President Nixon, which defined *Cannabis Sativa* (hemp inclusive) as a schedule I controlled drug or substance (18), and reclassified hemp as an agricultural commodity under the US federal law. This new improvement implies that the hemp plant can enjoy similar benefits with other agricultural commodities. Since hemp was no longer banned from being cultivated, individuals and businesses could obtain licenses to grow hemp for commercial purposes, legally transport hemp biomass throughout the United States, and of course, have access to low crop insurance costs (5, 20, 21).

In 2014, before the implementation of the Improvement Act of 2018, only states that had legal hemp production policies authorized the cultivation of industrial hemp by its state department of agriculture and local research institutions for research purposes under the pilot program provision of the Agricultural Improvement Act of 2014 (also known as the 2014 Farm Bill) signed into law by President Obama to study the beneficial importance of hemp (1).

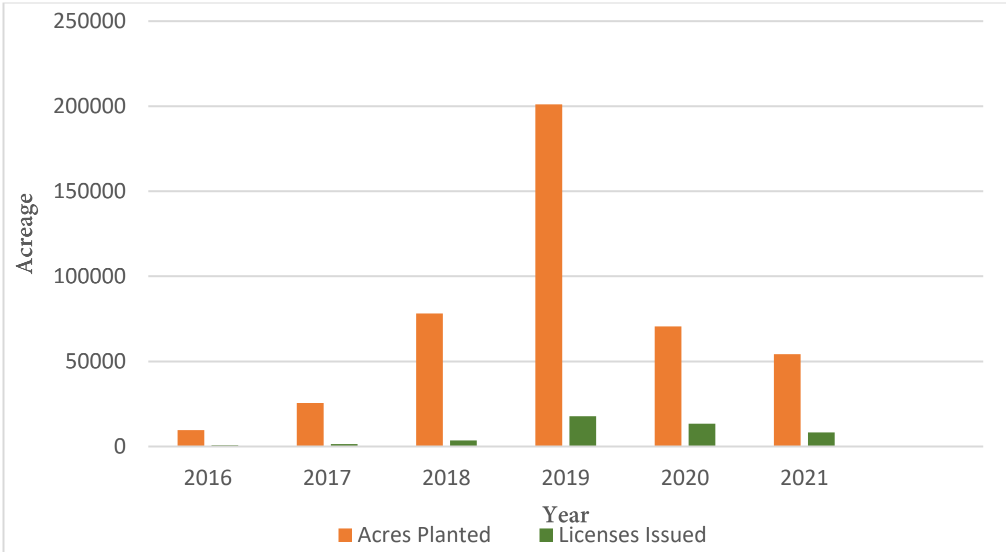

Figure 3-1 Table 3-1 US Hemp Acreage from 2016 to 2021. Source: Vote Hemp

Figure 3-1 shows the exponentially increasing trend of hemp acreage following the introduction of the pilot programs introduced by the 2014 Farm Bill. The acreage of hemp and number of licensed growers peaked in 2019 and decreased steeply in 2020 by over 150 percent (34). The market was extremely oversupplied with hemp biomass than demanded. The oversupply shock created an imbalance in the demand and supply leading to a declining trend in the price of hemp biomass and CBD products. The downward trend in price of hemp and hemp-based products (as shown in Figure 3-4 and 3-5) is expected to continue until there is an equilibrium between the demand and supply (35). According to PanXchange report (2020), a spitting percent (4.4%) of the total hemp acreage (201,126) in 2020, estimated at approximately 3000 acres was required to satisfy the US cannabinoid market demand (36). The acreage trend and hemp biomass production surge was motivated by the outcome of the pilot program and research revealed that every component of the plant has economic uses. The hemp stalk is a source of fiber and hurd, which can be used in making textiles, bioplastics, ropes, paper, and its byproduct can serve as animal bedding in livestock pens and organic compost in crop farms (7, 8). Hemp seed is a source of oil, seed cake, and hemp hull. The oil can be used for cooking oil and raw materials in the cosmetics (body care products) and chemical (paint) industries. It can also serve as a dietary supplement ingredient in animal feed production because of its rich fatty acid – omega 3 and 6 fatty acids. The plant leaves and flowers are sources of cannabidiol (CBD), and the remnant of the flower and leaves (roughages) after CBD extraction can serve as a source of animal feed ingredients, given that it has a rich crude protein content (9).

According to a latest national hemp report by the National Agricultural Statistics Service (NASS), the field acreage of hemp in 2021 has declined to 54,152 acres accounting for a total hemp production value of 712 million dollars, and hemp grown under a protected space of 15.6 million square feet was valued at 112 million dollars (37). This is represented in Figure 3-2 and 3-3.

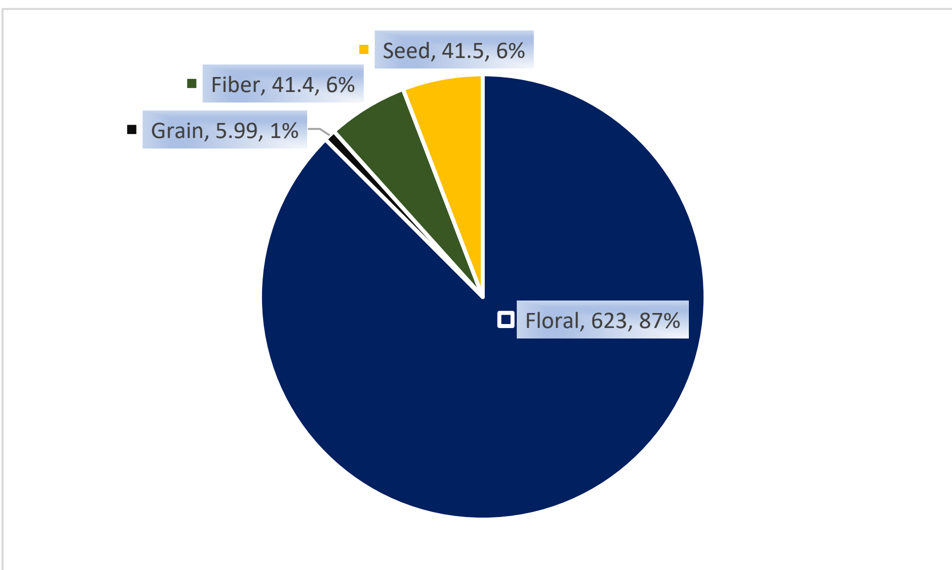

Figure 3-2 Value of Industrial Hemp grown in the open field in 2021. Source: NASS, USDA

The total floral hemp grown in the field in 2021 weighed 19.7 million pounds and was valued at 623 million dollars, hemp grain gross weight was 4.37 million and was valued at 5.99 million dollars. A total of 33.2 million pounds of hemp fiber and 18.6 million pounds of hemp seeds were produced and were valued at 41.4 and 41.5 million dollars, respectively.

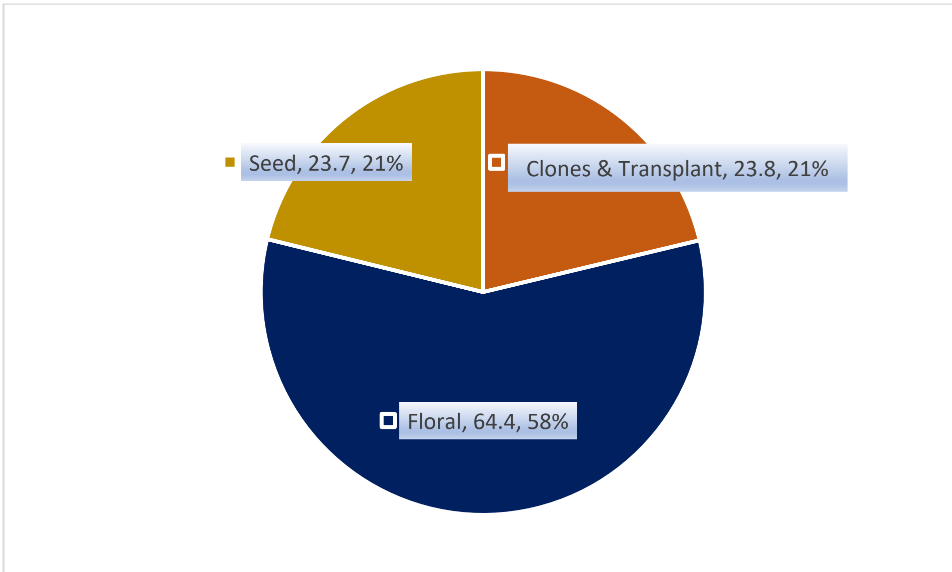

Figure 3-3 Value of Industrial Hemp grown in the protected space in 2021. Source: NASS, USDA

Hemp production in the protected area accounted for 310,000 pounds of hemp grown for floral and 4,059 pounds of hemp grown for seed valued at 64.4 and 23.7 million dollars, respectively. The total clones and transplants produced under the protected area were 20.2 million plants valued at 23.8 million dollars.

Unlike the early 1900s, when hemp was majorly renowned for its fiber, the present hemp supply chain is diversified with differentiated hemp-based value-added products for niche markets. In addition, there has been intense research and development of industrial hemp to explore and maximize the economic potential of hemp to establish a strong demand and create a hemp market. One of the research project is the projection of hemp as an animal feed ingredient because of its rich nutritional protein and fatty-acid content (10).

The crude CBD oil extract can be modified and refined into value-added differentiated products with alternative uses. Some of the refined CBD products are full and broad-spectrum distillate, THC-free distillate, and Isolate. The hemp biomass is cultivated by the farmers and sold to the processing industry as a raw material. The processing industry employs factors of production and other required inputs to create the final product for the consumer and/or intermediary product for a third industry in the supply chain (38). Figure 3-4 and 3-5 shows the price trend of hemp biomass and hemp value-added products, respectively from the period of industrial hemp legalization to the current period.

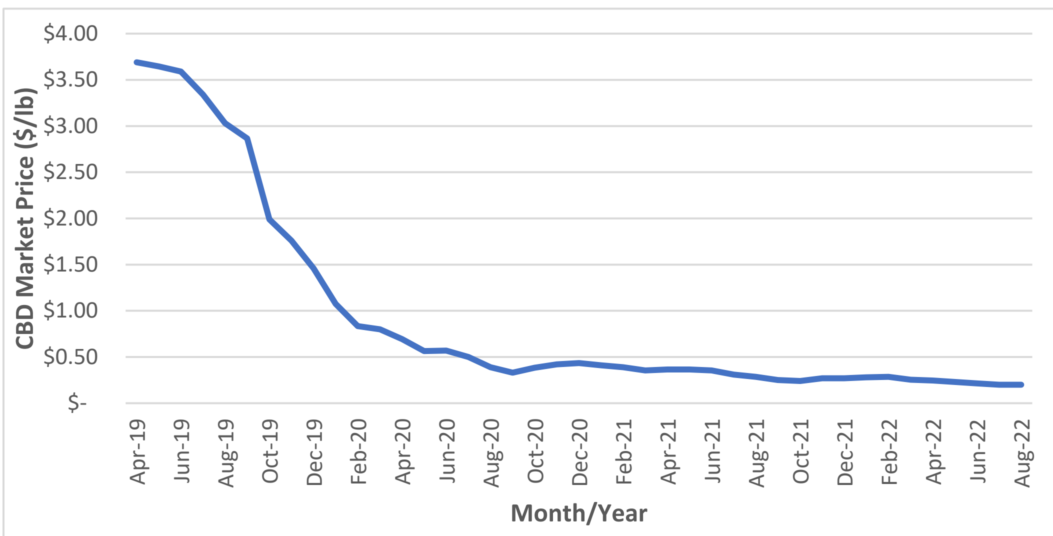

Figure 3-4 Price Trend of Hemp Biomass in the United States from April 2019 to August 2022. Source: New Leaf Data Service

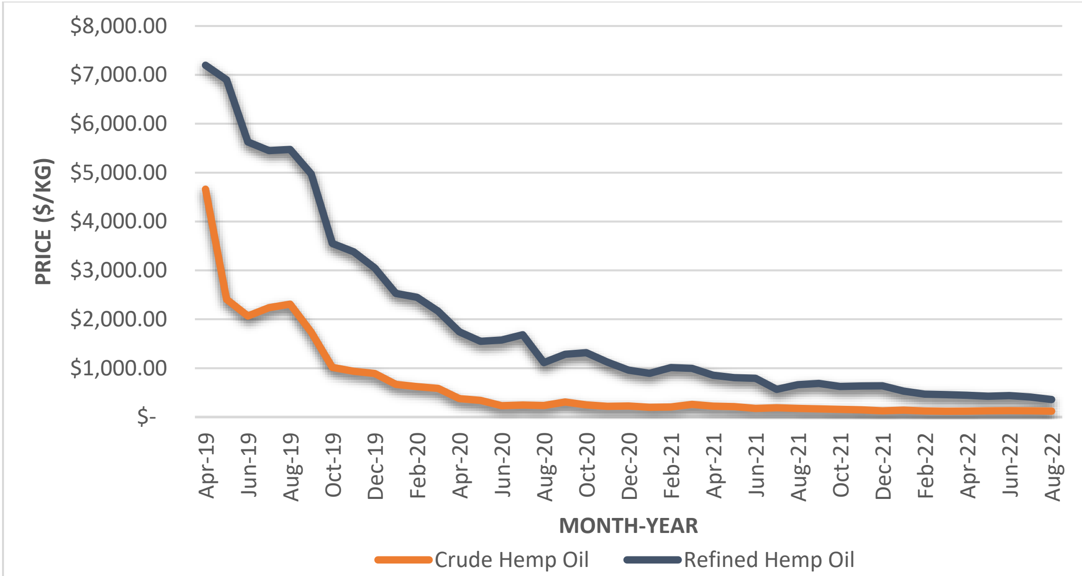

Figure 3-5 Price Trend of CBD crude hemp oil and refined CBD hemp oil Aggregate in the US from April 2019 to August 2022. Source: New Leaf Data Service

The Agricultural Marketing Resource Center (AMRC) defined agricultural value-added as – modifications to the physical form of an agricultural product, changes in the production process to improve the overall value of the ultimate product and marketing a product based on its differentiated and unique qualities to meet the taste of the niche market (38).

3.3 Research Objective

Price is the principal factor interconnecting various levels of the markets (39). The core objective of the research is to investigate the speed of price adjustment in the presence of external factors at different stages of the supply chain. We examined dynamic price adjustments and the possible presence of asymmetric price transmission across the hemp supply chain. The hemp supply chain in this research is limited to the farm – producers of the primary commodity (hemp seed, flowers, and leaves), the Processor I – extractors of the crude hemp oil from the hemp biomass, and the processor II – refiners of crude hemp oil into refined forms (THC free, broad and full spectrum distillates and Isolates). The price behavior along the supply chain will show the effects of an exogenous shock on different stages of the hemp supply chain and also provide information on the efficiency of the market at different stages of the hemp value chain (40). This research attempts the answer the research questions below:

i. What is the effect of price changes at each level of the hemp value-added supply chain on other phases of the supply chain?

ii. Is there a significant lag in the speed of price adjustments along the hemp value-added supply chain?

The hemp market is a new and volatile market, given that the production and processing of *Cannabis sativa* (industrial hemp inclusive) was banned for over fifty years in the United States until the recent 2018 Farm Bill. We investigated how quickly different US hemp supply chain stages adjusted their prices in response to an external shock. Also, we studied how the price change at each stage affects the prices at the other stages of the vertically integrated hemp market. For example – At the production level, how does the primary product (hemp biomass) price respond to changes in the price change of the intermediary and refined finished product at the value-added level

The outcome of this research will improve the understanding of price interactions and the speed of price adjustments in the US hemp market. Investors will have access to information regarding the degree of market price stability at each phase of the commodity supply chain, i.e., the speed at which each level of the supply chain will adjust its price in the presence of external shocks. Investors will be guided by this information to make better investment decisions.

3.4 Literature Review

3.4.1 Vertical Price Transmission

The speed, nature, and magnitude of price adjustments to market shocks at different phases of the supply chain describe the vertical price relationship. Depending on the shock's nature (positive and negative), the price may be transmitted through the supply chain at an asymmetric or symmetric speed and magnitude. The mechanism of asymmetric price transmission is expressed in Figure 3-6.

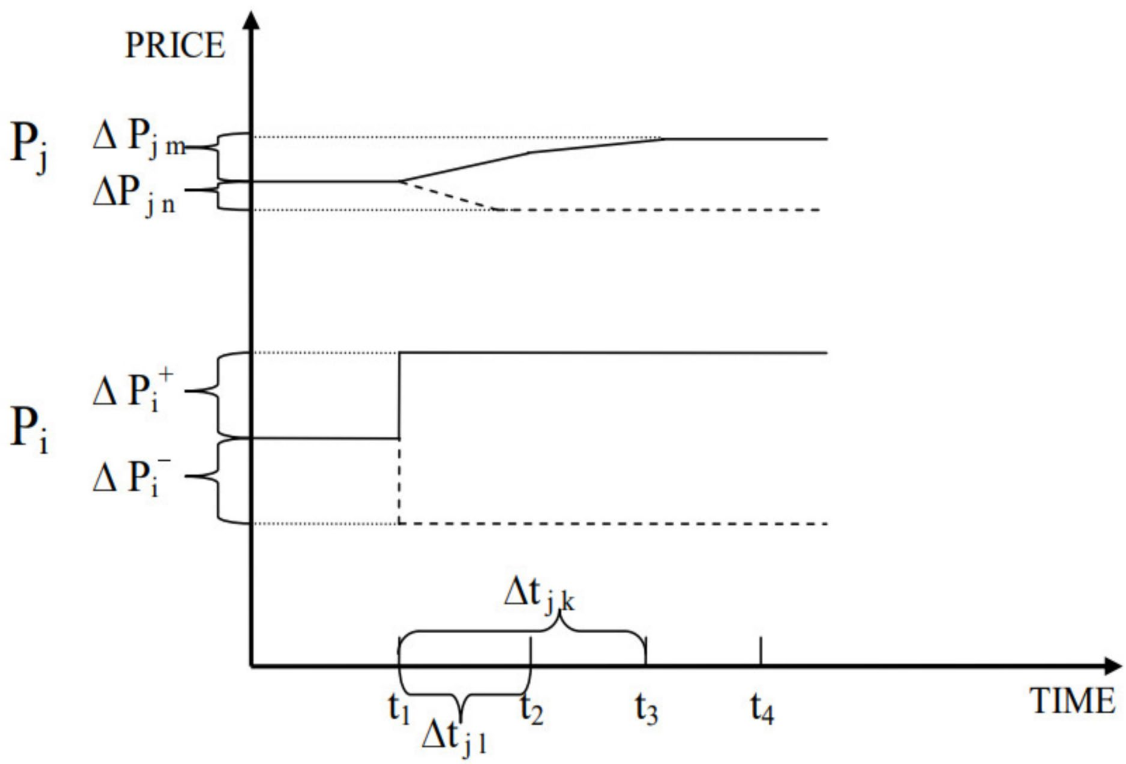

Figure 3-6 Illustration of asymmetric vertical price transmission. Source: Analysis of Price Transmission along the Food Chain, OECD Food, Agriculture, and Fisheries.

Figure 3-6 illustrates an asymmetric price transmission along two levels of a marketing channel (production level and retail level). The shocks illustrated in Fig 7 are positive $\Delta \boldsymbol{P}^{+}$ and negative $\Delta \boldsymbol{P}^{-}$ shocks. Both shocks are equal and represent the magnitude (size) of the shocks to the producer price in period $\boldsymbol{t_1}$. $\boldsymbol{P_i}$ and $\boldsymbol{P_j}$ represent the producer price and adjusted retail price, respectively. In the presence of an external shock to the producer price at the production level, the impulse is transmitted to the retail price along the marketing channel. $\Delta \boldsymbol{P_{jm}}$ and $\Delta \boldsymbol{P_{jn}}$ are the magnitude of shocks to the retail level, where $\Delta \boldsymbol{P_{jm}}$ represents the retail price adjustment to a negative producer price, and $\Delta \boldsymbol{P_{jn}}$ represents the adjustment of the retail price to a positive price producer price. Δt_{jk} is the retail price adjustment time lag to the positive producer price, while $\Delta \boldsymbol{t_{jl}}$ represents the retail price adjustment time lag to the negative shock on the producer price.

The positive shock on the producer price causes a positive change in adjusted retail price over some time, Δt_{jk}. Alternatively, a negative shock on the producer price triggers a response in the adjusted retail over a period of time, Δtjl. The relative increase in the producer price in the incidence of a positive shock is greater than the adjusted increase in the retail price, $\Delta P_i^+ > \Delta P_{jm}$. In the incidence of a negative shock, the relative decrease in producer price is greater than the adjusted decrease in adjusted retail price, $\Delta P_{jn} > \Delta P_i^-$.

The effect of a positive price shock is transmitted at the retail level over a longer period ***(*$\Delta \boldsymbol{t_{jk}}$*).*** Conversely, the effect of a negative price shock is transmitted to the retail price over a short period ***(*$\Delta \boldsymbol{t_{jl}}$*).*** $\Delta \boldsymbol{P_{jm}} > \Delta \boldsymbol{P_{jn}}$, this implies effects of the positive shocks are more reflected in the adjusted retail price than the negative shock effects (40).

Peltzman (2000) has argued that price asymmetry is a rule among agents in the marketing channel, given that asymmetric price transmission is a frequently obtainable outcome in most producers and consumer markets (41).

3.4.2 Empirical Research on Price Transmission

Kharin used monthly farm-gate and retail price data that spanned over a decade to investigate the vertical price transmission along the Russian dairy supply chain. His research employed the autoregressive distributed lag (ARDL) model and found no co-integration or relationship between the farm-gate and retail price and hence, estimated only the short-run relationship between the two variables – farm-gate and retail price. The granger test shows a unidirectional causality from retail to farm-gate prices. This implies that a change in retail price will trigger a change in farm-gate price and not the opposite. The result of the research revealed inefficient price transmission from one level of the supply chain to another. Hence, the researcher agreed with the existing idea that the Russian dairy retailer has market power in the Russian dairy industry (42).

Odiase *et al.* used monthly import and retail price data for two decades to investigate the effect of COVID –19 on the vertical price transmission in the US banana supply chain. They employed the Augmented Dickey-Fuller and Phillip Peron's unit root model to test the stationarity nature of the data, the Zivot Andrews breakpoint test to check for the presence of structural breaks, and the Johansen and ARDL co-integration test to check the relationship between the time series data. Their research also employed the historical decomposition graph to estimate the magnitude of price adjustment between both levels of the marketing channel. Their result showed price asymmetry, with the retail level as the market power taking the most advantage of the negative price shock caused by COVID – 19 pandemic while the import level and the consumers predominantly bore the burden of the shock (43).

Rajcaniova et al. examined vertical price transmission along Slovakia's food chain for milk, beef, pork, chicken, and potatoes. They analyzed the relationship between variables using the Johansen co-integration test and found out that all prices were cointegrated except for beef which implied that long-run equilibrium between producer and retail prices across all food commodities (beef excluded). They employed the Gregory-Hansen test to check for structural breaks in the price series. Their results indicated a strong asymmetric price transmission for milk, apples, and potato commodities and a weak asymmetrical price evidence for pork and chicken (44).

Sundaramoorthy et al. used monthly price data to examine integration and vertical price transmission in the Indian cotton-based textile value chain – raw cotton, cotton yarn, and cotton cloth. They used correlation analysis and the Johansen co-integration test to study the price linkage between the primary product and value-added commodities in the cotton supply chain. They adopted the Augmented Dickey-Fuller test to check the presence of unit roots using intercept, trend and intercept, and none. The VAR model was used to identify optimal lag based on the Schwartz Information Criterion (SIC). The outcome of the Granger causality test revealed that the price of the primary product (raw cotton) granger causes cotton yarn, and the cotton yarn granger causes the price of the final product (cotton cloth). This is evidence of a one-directional price transmission i.e. any change in the price of cotton (primary product) will influence the price of yarn (intermediary product), which will influence the price of cotton cloth (final product). Given that the prices across the cotton value-added supply chain were cointegrated, the researchers employed the vector error correction model to analyze the speed of price adjustments in the incident of an exogenous shock. Their research gave evidence of market integration and connectedness which means that a change in each phase of the cotton value-added supply chain will affect other phases of the commodity supply chain (45).

3.5 Conceptual Framework and Estimation Approach

Several researchers have adopted the Wolffram and Houck (46, 4) model in the study of vertical price transmission. Based on the Wolffram-Houck model, the relationship between the price series – hemp biomass, crude hemp, and refined hemp oil price, can be specified mathematically as:

$$\sum_{t=1}^{T} \Delta \boldsymbol{Y}_{i,t} = \beta_0 + \beta^{+} \sum_{t=1}^{T} \Delta \boldsymbol{X}_{i,t}^{+} + \beta^{-} \sum_{t=i}^{T\tau} \Delta \boldsymbol{X}_{i,t}^{-} + \varepsilon_t \quad - \quad - \quad - \quad 1$$

where: ΔX^{+} and ΔX^{-} show positive and negative changes in prices, respectively, β_0, β^{+}, and β^{-} are coefficients (If β^{+} and β^{-} are equal, then the price transmission is symmetric), τ is the period.

The major limitation of the Wolffram-Houck model is that it ignores the non-stationarity nature of time series. The non-stationarity nature of time series data causes spurious and inconsistent regression. Simply put, first-order autocorrelation is the limitation of research that was analyzed using only the only "Wolffram-Houck" model specification (48).

Hence, the stationarity test was employed in this research to avoid spurious and inconsistent regression. Then, an appropriate model was chosen to check for co-integration among the price series. The widely adopted stationarity test – Augmented Dicker Fuller (ADF), was used in this research to test the stationarity nature of the variables. The ADF assumes that a series follows an autoregressive (AR) process to investigate the potential of higher-order correlation. The null hypothesis of the ADF indicates that the series is not stationary, which implies that the series has a unit root, and both the mean and variance are not constant over time (49). The ADF model is specified in equation 2.

$$\Delta Y_t = \alpha_0 + \delta_i Y_{t-1} + \sum_i^p \boldsymbol{\alpha}_I \Delta Y_{t-1} + \varepsilon_t \qquad - \quad - \quad - \quad 2$$

The Johansen method, which hinges on the relationship between the matrix's rank and its root attributes, is frequently used for estimating co-integration in time series data (50, 51). However, this research employed the Autoregressive Distributed Lag (ARDL) because the series were stationary at different levels. Also, ARDL performs better for small sample size data (52, 53). The generalized form of the Autoregressive model is specified in equation 3:

$$\Delta Y_t = \alpha_0 + \sum_{i=1}^{p} \Delta \boldsymbol{\delta}_i Y_{t-1} + \sum_{i=1}^{q} \Delta \boldsymbol{\beta}_i X_{t-1} + \varepsilon_{jt} \qquad - \quad - \quad 3$$

where: p is the optimal lag for the dependent variable, and q is the optimal lags for the explanatory variables

The null hypothesis of the ARDL bounds test for co-integration denotes that there is no co-integration among the variable. The bounds test hypothesis is defined mathematically as:

Null hypothesis H_0: $\boldsymbol{\beta_{1i} = \beta_{2i} = \beta_{3i} = 0}$ (Short-run relationship exists among the variables)

Alternative hypothesis H_A: $\boldsymbol{\beta_{1i} \neq \beta_{2i} \neq \beta_{3i} \neq 0}$ (Long-run relationship exists among the variables)

The *Engle-Granger Representative Theorem* states that if the series are co-integrated, they will be most efficiently represented by an error correction model specification to estimate the long-run relationship. However, if the series is not co-integrated, only the short-run relationship between the variable series can be ascertained (40).

The Vector Error Correction (VEC) model of the ARDL, which is specified in equation 4 was employed, given that the series was significantly co-integrated.

$$\Delta Y_t = \alpha_0 + \sum_{i=1}^{p} \Delta \boldsymbol{\beta}_i Y_{t-1} + \sum_{i=1}^{q} \Delta \boldsymbol{\beta}_j X_{t-1} + \varphi_i Y_{t-1} + \varphi_j X_{t-1} + \varepsilon_t \qquad - \qquad 4$$

where:

$\mathbf{Y_t}$**,** $\mathbf{X_t}$ is a p-element vector of observations of all variables in the system at the time *t*,

$\boldsymbol{\alpha_0}$ is a vector of intercept terms

$\mathbf{B_i}$**,** $\boldsymbol{\beta_j}$ represents the dynamic short-run coefficients

$\boldsymbol{\varphi_i}$*,* $\boldsymbol{\varphi_j}$ are long-run coefficients and

$\boldsymbol{\varepsilon_t}$ is the white noise or error term

This research uses a 3 x 1 matrix representing the three price series (hemp biomass, crude oil, and refined oil prices). All variables should be non-stationary at all levels. The co-integration requires that the β matrix contain parameters such as Zt, where $Zt = \beta' Xt$ is stationary. The speed at which each variable changes to return to its respective long-run equilibrium after a temporary shock is represented by the α matrix, while the β matrix contains the co-integration vector representing the underlying long-run relation (54-58). The entire research method selection is summarized in Figure 3-7.

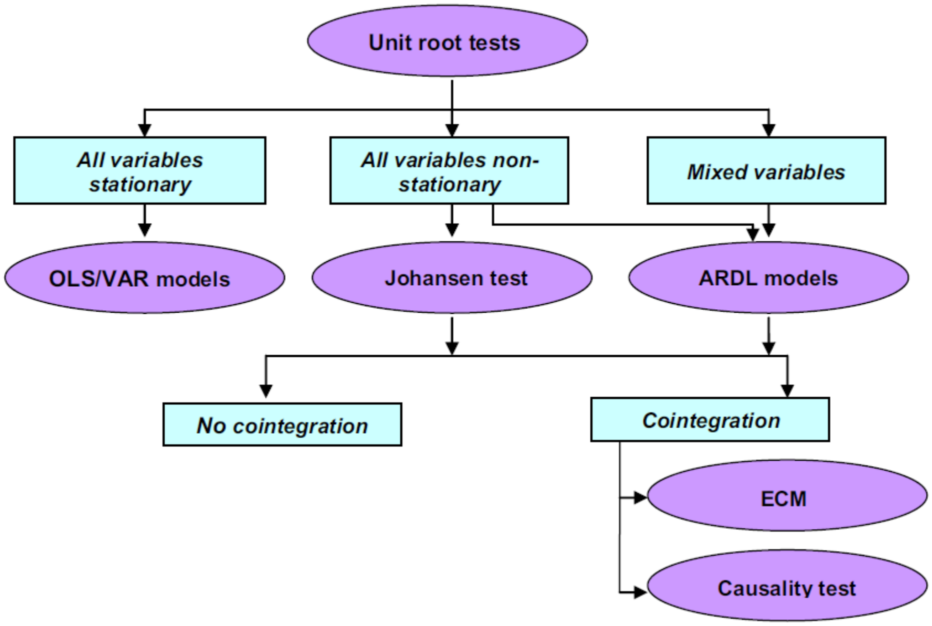

Figure 3-7 Method selection for time series data. OLS: Ordinary least squares; VAR: Vector autoregressive; ARDL: Autoregressive distributed lags; ECM: Error correction models

3.6 Data Description

The monthly price data across the value-added marketing channel, i.e., from the primary product (hemp biomass) to the intermediary (crude CBD hemp oil) and final product (refined CBD hemp oil) used in this research, was obtained from New Leaf Data Services (NDLS). The refined CBD hemp oil price is approximated average of all finely refined CBD products – full and broad-spectrum distillates, THC free distillates and Isolates. The price data spanned from April 2019 to August 2022 across of price data variables. Table 1 presents descriptive statistics of the price series, and Fig 3-7 depicts the price trends of value-added hemp products – THC free distillates, CBD Isolate, Full and broad spectrum CBD oil and the price average of the aggregate value-added CBD products – refined CBD aggregate.

Table 3-2 Descriptive Statistics of continuous hemp price data (from 2019 to 2022)

	Hemp Biomass	Crude Hemp Oil	Refined Hemp Oil
Mean	6.98	629.71	1897.46
Median	2.93	225	1012
Maximum	27.68	4661	7197
Minimum	1.5	119	358
Standard Deviation	8.25	922.16	1901.87
Skewness	1.63	2.64	1.51
Kurtosis	4.12	10.48	4.1

Source: Research Calculation. All nominal data are in dollars per pound.

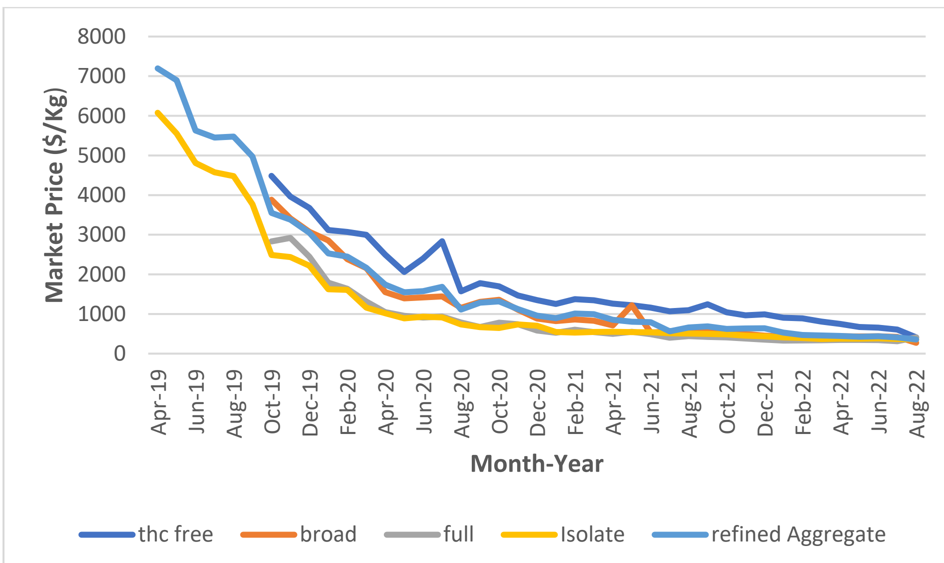

Figure 3-8 Price trend of individual value-added hemp products and its aggregate average

3.7 Empirical Results and Discussions

Before doing the pass-through regressions, it is required to determine whether the time-series data are stationary or non-stationary. The study used the Augmented Dickey-Fuller test to ascertain the stationary nature of the data sets, and the results are reported in Table 3-2.

Table 3-3 Stationarity Test Result

Variable	Intercept				Trend and intercept			
	Level		First difference		Level		First difference	
	t-stat	p-value	t-stat	p-value	t-stat	p-value	t-stat	p-value
HB	-13.48[a]	0			-2.422	0.363	-7.122[a]	0
Log(HB)	-2.551	0.112	-4.055[a]	0.003	-0.95	0.94	-4.604[a]	0
CB	-2.439	0.139	-9.279[a]	0	-2.422	0.363	-7.122[a]	0
Log(CH)	-2.495	0.124	-6.670[a]	0	2.513	0.321	-7.174[a]	0
RH	-5.459[a]	0.001			-3.301	0.081	-3.474[c]	0.057
Log(RH)	-2.573	0.107	-6.967[a]	0	-1.343	0.862	-7.718[a]	0

Test critical values at 1% are 3.6 and 4.2 at intercept, and trend and intercept, respectively. a and c indicate significance at 5% and 10% respectively.

From the Augmented Dickey-Fuller test unit root test **with intercept**, the hemp biomass and refined hemp oil prices series were found to be integrated at Level while the crude hemp oil price series at first difference while the Augmented Dickey-Fuller unit root test with **trend and intercept** has all the series integrated at order one. Also, all the natural log of the price series data was integrated at first difference. Given that the price series are integrated at different orders, the autoregressive distributed lag was used to check the long-run equilibrium across the series, and the results were reported in Tables 3-3, 3-4, 3-5, and 3-6. However, the Vector autoregressive (VAR) model is employed first to determine the optimal lag using model order selection criteria such as: Akaike Information Criterion (AIC), Schwarz Bayesian Criterion (SBC), or Hannan-Quinn Criterion (HQC). The Akaike Information Criterion (AIC) was chosen to obtain an optimal lag of three (3) because it gave the lowest value (59).

3.7.1 Co-integration Test

The ARDL employs F-statistics to test the null hypothesis of no co-integration among the time series variables. The F-statistics value was compared with upper and lower critical values. If the F statistics fell below the lower critical values, we fail to reject the null hypothesis and infer no co-integration among the variables. However, if the F-statistics is greater than the upper critical value, we reject that hypothesis and conclude that co-integration exists among the variables. Furthermore, the test was inconclusive if the F-statistics fell between the upper and lower bound critical values (60-62).

Table 3-4 ARDL Co-integration Test (F-statistics)

Model	F-statistics	Significance	Upper I(1)	Lower I(0)	Decision
Hemp Biomass	8.077	1%	6.36	5.15	Co-integration
Crude Hemp Oil	9.4	1%	6.36	5.15	Co-integration
Refined Hemp Oil	1.008	Not sig.	6.36	5.15	No co-integration

Source: Research findings

Hemp Biomass (HB) = f (Hemp Biomass (HB), Crude Hemp Oil (CH) + Refined Hemp Oil (RH) + ε_t

$$HB_t = \alpha_0 + \delta_1 HB_{t-1} + \delta_2 CH_{t-1} + \delta_3 RH_{t-1} + \sum_{i=1}^{p} \boldsymbol{\beta}_1 \Delta HB_{t-1} + \sum_{i=1}^{p} \boldsymbol{\beta}_2 \Delta CH_{t-1} + \sum_{i=1}^{p} \boldsymbol{\beta}_3 \Delta RH_{t-1} + \varepsilon_t$$

\- 5

Table 3-5 Short-run and Long-run ARDL Test Results

Variable	Coefficients	t-stats	Prob
Estimated Short-run coefficients model: Δlog Hemp Biomass (3,3,1)			
Δ(log(Hemp Biomass(-1))	0.479[a]	3.834	0.001
Δ(log(Hemp Biomass(-2))	0.22	1.702	0.1
Δ(log(Crude Hemp Oil))	0.067	0.801	0.43
Δ(log(Crude Hemp Oil(-1))	-0.118	-1.203	0.239
Δ(log(Crude Hemp Oil(-2))	-0.209[a]	-2.66	0.013
Δ(log(Refined Hemp Oil)	0.258[a]	2.456	0.021
Estimated Long-run coefficients of the ARDL (3,3,1)			
log(Crude Hemp Oil)	0.811[a]	7.058	0
log(Refined Hemp Oil)	0.07	0.536	0.596

a: rejection of the hypothesis at 5% level of significance. Source: Research findings.

The result from Table 3-4 shows that in the short run, ceteris paribus, a percentage increase in the first lag of hemp biomass price, and refined hemp oil price is associated with a 0.47 and 0.25 increase price of hemp biomass, respectively, at a 1 percent level of significance. In the long run, an increase in crude hemp oil price positively impacts the hemp biomass price at 1 percent significance level. Ceteris paribus, a percent increase in the price of crude hemp oil will increase the price of hemp oil by 0.81 dollars.

$$CH_t = \alpha_0 + \delta_1 CH_{t-1} + \delta_2 HB_{t-1} + \delta_3 RH_{t-1} + \sum_{i=1}^{p} \beta_1 \Delta CH_{t-1} + \sum_{i=1}^{p} \beta_2 \Delta HB_{t-1} + \sum_{i=1}^{p} \beta_3 \Delta RH_{t-1} + \varepsilon_t \quad - 6$$

Table 3-6 Short-run and Long-run ARDL Test Results

Variable	Coefficients	t-stats	Prob
Estimated Short-run coefficients model: Δlog Crude Hemp Oil (1,0,1)			
Δ(log(Crude Hemp Oil(-1))	0.451[a]	3.316	0.002
Δ(log(Hemp Biomass	0.405[a]	2.609	0.013
Δ(log(Refined Hemp Oil)	0.351	1.815	0.078
Δ(log(Refined Hemp Oil(-1))	-0.21	-1.087	0.284
Estimated Long-run coefficients of the ARDL (1,0,1)			
log(Hemp Biomass)	0.737[a]	3.795	0
log(Refined Hemp Oil)	0.257	1.282	0.208
log(Crude Hemp Oil)	0.811[a]	7.058	0
log(Refined Hemp Oil)	0.07	0.536	0.596

a: rejection of the hypothesis at 5% level of significance. Source: Research findings.

The result from Table 3-5 shows that in the short run, ceteris paribus, a percent change in the first lag of crude hemp oil and hemp biomass price is associated with a 0.45 and 0.40 increase in the price of crude hemp oil, respectively at a 1 percent level of significance. In the long run, an increase in hemp price positively impacts the crude hemp oil price at 1 percent significance level. Ceteris paribus, a percent increase in hemp biomass price will increase the crude hemp oil price by 0.73 dollars.

The result from Table 3-6 shows the first and second lag of refined hemp oil price significantly impacts refined hemp oil price. For example, a percent change in the first and second lag of refined hemp is associated with a 0.40 and 0.47 decrease in the price of refined hemp oil at a 1% level of significance in the short run.

$$RH_t = \alpha_0 + \delta_1 RH_{t-1} + \delta_2 CH_{t-1} + \delta_3 HB_{t-1} + \sum_{i=1}^{p} \beta_1 \Delta RH_{t-1} + \sum_{i=1}^{p} \beta_2 \Delta CH_{t-1} + \sum_{i=1}^{p} \beta_3 \Delta HB_{t-1} + \varepsilon_t \quad - 7$$

Table 3-7 Short-run and Long-run ARDL Test Results

Variable	Coefficients	t-stats	Prob
Estimated Short-run coefficients model: Δlog Refined Hemp Oil (3,1,0)			
Δ(log(Refined Hemp Oil(-1))	-0.406[a]	-2.928	0.006
Δ(log(Refined Hemp Oil(-2))	-0.470[a]	0.132	0.001
Δ(log(Hemp Biomass))	0.245	1.378	0.178
Estimated Long-run coefficients of the ARDL (3,1,0)			
log(Hemp Biomass)	-1.249	-0.874	0.389
log(Crude Hemp Oil)	1.908	1.512	0.141

a: rejection of the hypothesis at 5% level of significance. Source: Research findings

3.7.2 Causality Test

The pairwise granger causality was tested across the variables – hemp biomass (HB), crude hemp oil (CH), and refined hemp oil prices (RH), to identify the variable that was useful in predicting the price of other variables in the market. The logarithmic functional form of each variable price was used to reduce outlier effects. The result of the causality test presented in Table 7 shows that the primary product (hemp biomass) granger causes the price of the intermediary product (crude hemp oil). This implies that the hemp biomass price can be relied upon to predict the crude hemp oil price. Hence, we reject the null hypothesis that hemp biomass prices do not granger cause crude hemp oil prices.

Table 3-8 Granger causality test results

Null Hypothesis	Observation	F Statistics	Prob.
HB does not granger causes CH	38	5.85	0.02[a]
CH does not granger causes HB		1.55	0.22
RH does not granger causes HB	38	0.55	0.65
HB does not granger causes RH		0.3	0.82
RH does not granger causes CH	38	0.13	0.94
CH does not granger causes RH		0.55	0.65

a: significance at 5%. Source: research findings

3.7.3 Speed of Adjustments

The coefficient of adjustment speed explains how quickly the system returns to its long-run equilibrium after being affected by an external shock. The adjustment speed coefficient of the Hemp biomass and crude hemp price were significant, while the refined hemp oil price adjustment speed coefficient was statistically insignificant.

In the research, the speed of adjustment of biomass (–57%) and crude oil (–55%) price were statistically significant at 1% level, while the refined hemp adjustment speed (–0.13) was statistically insignificant. This implies that the deviation in price from long-run equilibrium in the preceding period is corrected in the present period at an adjustment speed of 57 percent and 55 percent for the farm-level primary product (hemp biomass) and the intermediary product (crude hemp oil), respectively. This indicates approximated asymmetric price relationship at the first and mid-stage of the value-added channel, i.e., a disequilibrium of the system due to a price change caused by a temporary shock is adjusted back to its equilibrium state in the long run at the same speed for the farm level and mid-stage products (hemp biomass and crude hemp oil). However, the final product (refined hemp oil) is asymmetric with hemp biomass and crude hemp oil price. The refined hemp oil adjusts back to long-run equilibrium after an external shock in the system at an insignificant adjustment speed of 13 percent.

This result shows that the first stage (farm) and mid-stage (processor I) are more efficient the final stage (Processor II) in the value-added marketing channel because its price is adjusted more quickly to equilibrium after an exogenous shock. This implies that the consumer predominantly bears the burden of the shock in the system. The results are presented in Table 3-8.

Table 3-9 Empirical estimates of speed adjustment

Variables	log(Hemp Biomass)	log(Crude Hemp Oil)	log(Refined Hemp Oil
Error Correction Term (ECT)	-0.5669[a] (-4.491)	-0.5489[a] (-4.034)	-0.1289 (-1.605)
R-squared	0.650	0.475	0.475
Adjusted R-squared	0.572	0.447	0.447
Akaike Criterion	-2.244	-1.095	-1.095
Schwarz Criterion	-1.899	-0.969	-0.969
Durbin Watson	2.025	1.74	1.74
F statistics	8.077	16.76	1.199
P (F statistics)	0.000	0.000	-0.329

a: rejection of the hypothesis at 5% level of significance. Source: Research findings.

3.7.4 Robustness Check

In this research, the robustness check was investigated using Breusch–Godfrey (BG) test, which is based on the Lagrange Multiplier (LM) test. The Breusch-Godfrey test is the best test for identifying autocorrelation. The BG test null hypothesis states that if the p value less than or equal to 0.05 at 5% level of significance, we conclude that there is no serial correlation in errors in the regression model. However, suppose the p value is greater than 0.05 at 5% level of significance. In that case, we reject the null hypothesis and conclude that the model is inefficient, and the ARDL error correction model's coefficients are biased because there is serial correlation in the errors in the regression model. The result of the BG test is reported in Table 3-9.

Table 3-10 Autocorrelation Test

Breusch Pagan Godfrey Autocorrelation Test	F Statistics	Prob (F Stat.)
log(Hemp Biomass)	1.725	0.13
log(Crude Hemp Oil)	1.199	0.3287
log(Refined Hemp Oil)	0.68	0.667

Source: Research finding

It is necessary to check the stability of model to confirm the accuracy of the statistiscal assumption of in the study. The autoregressive root characteristics of the polynomial is shown in Figure 3-8. The root characteristics polynomial is used to check the stability of the short run causality among endogenous variables in model (63). Since all points in the root characteristic graph fell within the boundary of the circle, it implies that the model is stable.

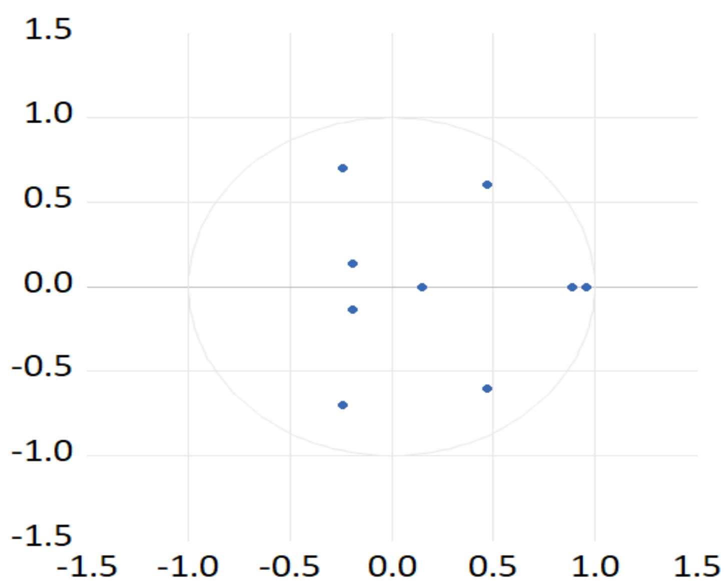

Figure 3-9 Inverse Roots of Autoregressive Characteristic Polynomial

3.8 Conclusion, Summary, and Policy Implications

The dynamic price adjustment in the value-added marketing channel – farm, processor I and processor II; of the hemp industry was analyzed in this study using monthly price series data ranging from April 2019 to August 2022. Different econometric models were employed at different stages of this research, such as the augmented dickey-fuller to test the stationarity nature of the datasets, autoregressive distributed lag to check for co-integration relationship among the variables and monitor the short-run and long-run relationship that exists among the time series, and the vector error correction model to estimate the price adjustment speeds and the pairwise granger causality test to determine the variable that was useful in the prediction of other variable price.

The research results show that the farm and processor I prices adjusted at an approximated symmetrical speed of 57 percent and 55 percent, respectively, while the processor II price adjusted asymmetrically from other phases of the value chain at an insignificant speed of 13 percent. The hemp market is presently experiencing a shock caused by oversupply of hemp biomass and hemp-derived products than demanded by its market. This shock can only be cancelled out with an increase in the demand of hemp and hemp derived products to meet supply.

A possible explanation delay in the speed of adjustment in the presence of external shock at the processor level in the marketing chain can be due to value-added agriculture and marketing advantage. Processor II purchase the intermediary product (crude hemp oil) and refines it into various form – full spectrum distillate, distillate broad spectrum distillate, tetrahydrocannabinol (THC) free distillate, and isolate; and alternatively creates different uses for the products. Processor II created a bunch of refined products with differentiated economic importance. Hence, this explains that this phase adjusts to negative shock slowly compared to the farm and processor I phase in the value chain. This research shows that the hemp industry is similar to other industries marketing chain where the retailers often possess market power and react mildly to negative market interferences and rapidly to positive market shocks. Like the refined and differentiated hemp product agent, retailers provide value-added services like a one-stop location for consumers to purchase all their needs ranging from groceries to clothing, credit services, and a variety of similar products and brands. This finding goes to show the merits of value-added agriculture.

With tons of investors looking to venture into the hemp commodity space, the outcome of this research suggests that the last stage of value-addition is the most stable and least volatile stage in the marketing channel to invest your money. This implies that a higher return-on-investment is highly likely in this phase of the hemp supply chain. The information from this research will enlighten producers on the need to allocate hemp acreage based on contracted demand for hemp biomass. There is a dire need to develop and establish more uses of hemp in the US to boost the growth of its domestic hemp market. The increase in the demand for hemp and its derived product will facilitate the growth of sustainable hemp market.

In general, some external factors that affect prices uniquely at different levels of the value-added chain are transportation and transactional expenses, economies of scale and scope, product differentiation, contracts, exchange rate, domestic policies and so on (40).

Cannabis Sativa (industrial hemp) production and processing has been legally prohibited for about half a century until 2014 and 2018 Farm Bill. Hence, this research was limited by small sample data for each variable time series. However, the research employed ARDL model which is a robust model for small sample data. Given that the hemp market is new and volatile, the author recommends a review of this paper over time using a more comprehensive array of datasets.

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VITA

Solomon E. Odiase

Education

B.S. Agriculture Economics and Extension Services, University of Benin, November 2018

Professional position

Graduate Research Assistant, University of Kentucky Department of Agriculture Economics. February 2021 – December 2022

Conference Presentation

Southern Agriculture Economics Association. Impact of COVID-19 on the Vertical Price Transmission in the US Banana Market. New Orleans, Louisiana.

Professional publication

Impact of COVID-19 on the Vertical Price Transmission in the US Banana Market. Sustainability Journal